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Carbon Capture and Storage in the Power Sector of Portugal and Spain

Lukas Fritz

Mestrado Integrado em Engenharia da Energia e do Ambiente

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Trabalho realizado sob a supervisão de

Prof. Dra. Dulce Boavida (LNEG, FCUL)

2011

Acknowledgments

I would like to thank Professor Dr. Dulce Boavida and Professor Dr. Jorge Maia Alves for their supervision and suggestions during this work and for their great support during my studies on the University of Lisbon.

Also, I would like to thank my colleagues at FCUL for all their support and friendship, which made my start in Lisbon very enjoyable. Special thanks to my sister Maria Fritz for her help in the revision of the thesis.

I owe my deepest gratitude to my girlfriend Ana Duarte, for being the main motivator during my studies and for inspiring me.

Furthermore I would like to thank my family and all my friends for the great support and motivation. Special thanks to my brother Matthias Fritz and my cousin Johannes Schmid for her unique and special way of supporting and motivating me in finishing my thesis.

Abstract

Portugal and Spain are still relying heavily in fossil fuels. In the year 2007 around 64% of Portugal's and 61% of Spain's total electricity generation was provided by conventional, fossil-fuel based power plants. Due to the high dependency of Portugal's and Spain's power sector on fossil fuels, the related CO_2 emissions of this sector are very high. To limit climate change to an acceptable level, where its consequences are limited to a minimum, it is necessary to define the cap in temperature increase with 2-degree Celsius, compared to pre-industrial level. To reach this ambitious target, carbon dioxide emissions of industrialized countries, including Portugal and Spain, have to be reduced by at least 80% by 2050. These changes will include a sharp increase in electricity generation out of renewable energy sources, strict energy efficiency measures and the induction of CCS technologies for coal- and gas-fired power plants.

The objective of the following study was to analyze the necessity and technical and economical viability of CCS systems for Portugal's and Spain's power sector, in order to decarbonize the Iberian power sector by 2050. For that purpose the carbon dioxide LPS (large point sources) of the power sectors and possible storage sides for CO_2 were identified and a source-sink matching analysis was performed by mapping the LPS sources and potential geological sinks to analyze the proximity of sources and sinks. Furthermore the future economic potential of RES for electricity production was identified. For that two different scenarios were developed. In a first scenario 60% of electricity generation will be covered by RES and the remaining 40% in even shares by CCS based coal- and gas-fired power plants. The second scenario assumes 80% RES and 20% CCS. For Spain in both scenarios nuclear power generation is considered with a share of 10%. In the last part of the thesis the economical parameters for different power generation technologies were analyzed and the Levelized Cost of Electricity Generation (LCOE) by 2050 calculated. As the results show, the break-even price for CO_2 certificates will be around 25 €/t in order to make coal based CCS power plants economical viable. For gas-fired power plants the break-even price is around 83 €/t.

Keywords: CCS, CO2, LPS, Portugal, Spain

Resumo

Portugal e Espanha são ainda caracterizados por uma forte dependência nos combustíveis fósseis. No ano de 2007, cerca de 67% da produção eléctrica total em Portugal foi gerada por centrais convencionais baseadas em combustíveis fósseis. Devido a esta forte dependência nos combustíveis fósseis, verificada quer no sector energético português, quer no espanhol, as emissões de CO_2 resultantes assumem valores elevados. De forma a ser possível limitar as alterações climáticas a um nível aceitável, minimizando o seu impacto, torna-se necessário definir o *cap* do aumento da temperatura a 2 graus Celsius, em relação ao nível pré-industrial. A fim de alcancar este ambicioso objectivo, as emissões de dióxido de carbono nos países industrializados, incluindo Portugal e Espanha, têm de ser reduzidas em pelo menos 80% até 2050. As alterações necessárias incluem um aumento acentuado da produção energética com base em fontes renováveis, rigorosas medidas para a eficiência energética e a introdução de tecnologias CCS para centrais de carvão e de gás.

O objectivo do presente estudo foi analisar a necessidade bem como a viabilidade técnica e económica das tecnologias CCS no sector energético em Portugal e Espanha, de forma a descarbonizar o sector de energia Ibérico até ao ano de 2050. Para o efeito, as LPS (*Large Point Sources*) de dióxido de carbono dos sectores energéticos, e possíveis formas de armazenamento de CO2 foram identificadas e uma análise de correspondência fonte-dreno foi efectuada pelo mapeamento das fontes de LPS e potenciais sumidouros geológicos, e analise da proximidade de fontes e sumidouros. Da mesma forma, o potencial económico futuro de RES para a produção de electricidade foi identificado. Nesse âmbito, dois cenários diferentes foram analizados. No primeiro cenário, 60% da produção eléctrica será proveniente de fontes energéticas renováveis enquanto os restantes 40% em igual proporção de centrais de carvão e de gás baseadas em tecnologias CCS. No segundo cenário considera-se 80% RES e 20% CCS. Para Espanha, em ambos os cenários, considera-se uma taxa de 10% de produção energética nuclear. Na parte final da tese, foram analisados os parametros económicos para tecnologias de produção energética diversas e calculados os *Levelized Costs of Electricity Generation* (LCOE) até 2050. Como os resultados demonstram, o preco *break-even* para os certificados de CO_2 será cerca de 25€/t de forma a tornar as centrais de carvão baseadas em CCS economicamente viáveis. No caso das centrais de gás, o preco *break-even* assume valores de aproximadamente 83€/t.

Palavras-chave: CCS, CO2, LPS, Portugal, Spain

Acronyms

CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CCGT	Combined Cycle Gas Turbine
CO_2	Carbon Dioxide
CSP	Concentrating Solar Power
ECBMR	Enhanced Coal Bed Methane Recovery
ECF	European Climate Foundation
EEA	European Energy Agency
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
EU – ETS	European Union Emissions Trading Scheme
GDP	Gross Domestic Product
GHG	Greenhouse Gases
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized Cost of Electricity Generation
LPS	Large Point Sources
LRMG	Long Run Marginal Costs
MEA	Mono-Ethanolamine
NAP	National Allocation Plan
NGCC	Natural Gas Combined Cycle
OPEX	Operational Expenditures
PSA	Pressure Swing Adsorption
RES	Renewable Energy Sources
SRMC	Short Run Marginal Costs

TPES	Total Primary Energy Supply
UNFCCC	United Nations Framework Convention on Climate Change

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1. Introduction

1.1 Background

Already in 1988 the Intergovernmental Panel on Climate Change (IPCC) was jointly established and its first assessment report on climate change was published in 1990, stating that emissions resulting from human activities are substantially increasing the concentration of greenhouse gases (GHG) and that these increases will enhance the greenhouse effect, resulting in an additional warming of the Earth´s surface.[1] As climate change is a global issue and its consequences are real, effective responses on a global level are needed to tackle it. By the definition of the IPCC, "climate change refers to a change in the state of climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period (decades or longer). It refers to any change in climate over time, whether due to natural variability or as a result of human activity."[2] This definition differs from the definition used by the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC defines it as "a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods."[3]

Climate change and its global effects on natural systems have great impacts on our society and human beings in general. Change of temperature and precipitation, the rise of sea level and extreme local weather events influence and harm our ecosystems, water resources, food security, settlements and society as well as human health. This leads to serious conflicts with our socio-economic development. Exactly this socio-economic development is the cause of the conflict due to misuse of our natural- and human resources which have influence on the climate process drivers such as greenhouse gases.[4] The influence parameters on our socio-economic development, such as technology, population, trade and many more, are the reason for anthropogenic drivers on climate change. These drivers have to be reduced in a sustainable way to limit the effects of climate change to an acceptable level. The mitigation of climate process drivers has a direct impact on the level of adaptation to climate change.

[1] IPCC (1990, p. XI)

[2] IPCC (2007a, p. 30)

[3] IPCC (2007a, p. 30)

[4] IPCC (2007a, p. 26)

The following schematic framework illustrates the linkages between anthropogenic climate change drivers, impacts of and responses to climate change as described above.

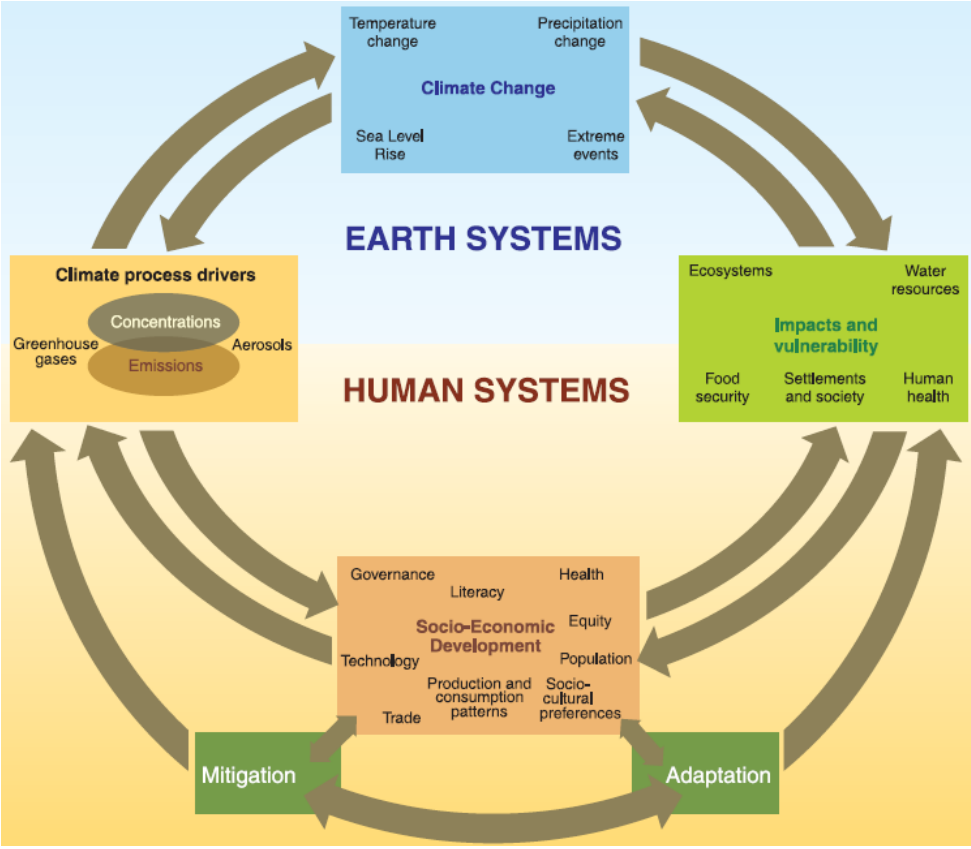

Figure 1.1: Linkage between anthropogenic climate change drivers, impacts of and responses to climate change (Source: IPCC – Intergovernmental Panel on Climate Change (2007), Climate Change 2007: Synthesis Report, URL: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf [10.01.2011])

An acceptable level of climate change, where its consequences are limited to a minimum, is to limit the temperature increase to 2-degree Celsius, compared to pre-industrial level. This is confirmed by the Fraunhofer Institute Systems and Innovation Research (Fraunhofer-ISI), which assumes that negative consequences of climate change remain limited and no tipping points of natural systems are reached with a temperature increase of 2-degree Celsius.[5] This restriction in temperature rise requires high efforts in mitigation and besides that considerable adaption to climate change effects. The Intergovernmental Panel on Climate Change expects a rise of sea level of 0.4 to 1.4 meters for a temperature increase of 2.0 to 2.4 degree Celsius compared to pre-industrial levels.[6] In order to reach this ambitious target, the European Union formulates the target of reducing GHG emissions by -50%

[5] Fraunhofer Institute Systems and Innovation Research (Fraunhofer-ISI) (2009, p. 3-4)

[6] IPCC (2007a, p. 67)

by 2050 compared to 1990 on a global level. This equals a necessary reduction of -80 to -95% by the industrialized countries by 2050.[7] This was the scientific basis when the leaders of the European Union and the G8 decided in July 2009 for the objective to reduce greenhouse gas emissions (GHG) by at least 80% by 2050 compared to 1990 levels. The abatement objective of 80 to 95% for Europe and other developed economies was set in October 2009 by the European Council.[8] This ambitious target results in substantial reductions of GHG in all sectors and likely translates to a requirement of an almost complete decarbonization of some sectors – like the power sector – in particular. This necessary decarbonization of the power sector results out of the structure (mainly large scale CO_2 point sources) of this sector and its high share on total GHG emissions.

1.2 Status Quo and the objective of the thesis

Within the different options of decreasing the worldwide greenhouse gas emissions, including carbon dioxide emissions, the option of carbon capture and storage for a reduction of CO_2 emissions within the large scale power sector is widely discussed. Obviously the implementation of CCS technologies doesn´t imply an avoidance of CO_2 as a gaseous product of the combustion process, but avoids the appearance of carbon dioxide as a pollutant (immission) in our atmosphere. By energy producers and policy makers this option is considered as a potential CO_2 reduction possibility especially for large scale CO_2 point sources (LPS) such as coal-fired power plants as well as a so called bridging technology during the time needed to base our energy supply on carbon free, renewable energy technologies. Though it is clear that no single measurement taken to reduce GHG is sufficient to tackle climate change and broad actions are needed, with CCS technologies the use of fossil fuels such as coal for power generation and combustion in industrial processes will continue well into this century. This is due to the fact that coal is a relatively abundant, cheap, available and globally distributed energy source and thus enhancing the security and stability of energy systems.[9] This is confirmed by the World Coal Institute who mentions that coal is located worldwide and can be found on each continent with the biggest reserves in the USA, Russia, China and India.[10] Transition economies, such as China and India, are searching to base their economy on cheap resources in order to fulfill their tremendously increasing energy demand and to ensure their energy supply. The combustion of coal in developing countries was the main reason of the increase of the global CO_2 emissions between 2006

[7] Fraunhofer Institute Systems and Innovation Research (Fraunhofer-ISI) (2009, p. 4)

[8] ECF - European Climate Foundation (2010, p. 3)

[9] Bachu (2007, p. 254)

[10] World Coal Institute (2005, p. 3)

and 2007.[11] Therefore especially in transition economies clean coal technologies and CCS can play a major role in reducing CO_2 emissions.

The objective of the following study is to analyze the feasibility of the implementation of CCS technologies as a possible pathway to go in order to tackle climate change and therefore to decarbonize the power sector of the Iberian Peninsula (Portugal and Spain). The feasibility will be studied on a technical, economical and energetic/ecological basis. This includes an analysis of the existing power sectors of the countries mentioned above to estimate the potentials and necessity for the implementation of CCS technologies.

The goal is to analyze the role of CCS in the transition of the power sector under an increasing penetration of renewable energy sources. Considered are the existing, stationary CO_2 large point sources within the power sector, as they are the main contributors on CO_2 emissions of the power sector and therefore possible applications for CCS. Basis for the identification of CO_2 LPS are the installations included in the National Allocation Plan II of the European Emissions Trading Scheme in the Kyoto Protocol commitment period 2008 until 2012. The assessment of the implementation of CCS as a possible carbon dioxide mitigation strategy has to be made on a technical, economical and energetic/ecological basis. Additional energy is required to remove, compress, transport and finally inject the CO_2 in its storage side. Furthermore the costs for the whole process chain (from source to sink) have to be considered. The implementation of CCS will also have a strong dependency on political will and therefore on political decision makers – regulatory and legal aspects are playing a major role. Decisions for or against CCS will also be defined by the social acceptance within the population. The analysis of CCS on a political and social level is not goal of the thesis.

1.3 Organization of the thesis

The first chapter focuses on the basics of global warming, the necessity of its mitigation and level of adaption to climate change. Furthermore the global and European GHG reduction commitments necessary to tackle climate change and its consequences for the power sector are mentioned. The aims of the diploma thesis are explained in the chapter "Status Quo and the objective of the thesis", where the future role of fossil fuels and CCS is explained. Chapter 2 focuses on the current state of CCS technologies and existing capture technologies and systems, opportunities for carbon dioxide transport and ways for long-term storage.

[11] IEA - International Energy Agency (2009a, p. 9)

In the following chapter 3 the author will analyze the anthropogenic, worldwide GHG emissions by its sector and gas and furthermore the carbon dioxide emission data of Portugal and Spain will be analyzed and stationary, large scale CO_2-emitters within the power sector identified to make a qualified statement about the possibilities and opportunities existing within the power sector of these countries to reduce their power sector related carbon dioxide emissions. The goal is to analyze the geographical matching between CO_2 sources and possible sinks.

In chapter 4 “Power sector of the countries researched” a close look is taken on the electricity sectors of the countries and their generation/fuel mix, to analyze the share of RES on generation and consumption and their dependency on imports. This is necessary to analyze the role of renewable energies in the power sector and their contribution for a decarbonized electricity generation by 2050.

In the following chapter 5 the author will analyze the role of RES and CCS within the power sector in the context of a carbon dioxide emissions reduction by 95% until 2050. Two different decarbonized pathways within the power sectors of Portugal and Spain will be studied and analyzed on a technical and economical scale. These pathways differ in their shares of a mix of renewable energy technologies, CCS technologies for fossil fuels (coal and gas) and, in the case of Spain, nuclear energy. The analysis of the pathways is based on the study “Roadmap 2050”, in which “business as usual” growth in electricity demand is avoided almost completely by applying aggressive energy efficiency measures.

The last chapter of the thesis concentrates on the analysis of the economical feasibility of CCS technologies in the Iberian power sector. The deployment of CCS technologies will strongly depend on the economical competitiveness with alternative/conventional electricity generation technologies. First of all the author will describe the influence of carbon prices on the electricity market (merit order) and how contribution margins of different conventional electricity generation technologies change due to higher carbon prices. In a second stage the development of life cycle cost of electricity generation (LCOE) for the different electricity generation technologies is researched. An attempt is made to estimate the LCOE by 2050 and to derivate the role of RES- and CCS-based electricity generation by 2050. Furthermore the uncertainty of carbon price- and fuel price development and their influence on LCOE by 2050 are considered in a sensitivity analysis.

2. State of the art of CCS technology

To store carbon dioxide it has to be separated from the flue-gas, compressed and transported to the sink. According to the IPCC, carbon capture and storage is defined as a process consisting of CO_2 removal from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere.[12] The removal of CO_2 always involves the separation of carbon dioxide from other gases. For this separation process different technical concepts applicable within the conventional power sector are available. These carbon dioxide capture concepts, the transportation of CO_2 from its source to the sink and the different storage concepts existing will be explained further in this chapter. CO_2 capture systems are likely to be applied mainly for LPS such as fossil fuel power plants, fuel processing plants and other industrial plants (iron, steel, cement and bulk chemicals production). The capture of CO_2 from small and mobile sources, as the residential and commercial building sector and the transportation sector, would be more difficult and expensive than from the already mentioned LPS.[13] This is confirmed by the European Energy Agency (EEA) which considers large stationary sources such as power generation or oil refineries as the best application of CCS, having large and concentrated streams of carbon dioxide emissions.[14] Therefore the following study will only focus on CCS systems for conventional LPS in the power sector.

For the transport of carbon dioxide to its sink it has to be compressed. This is due to the fact that any gas transported close to atmospheric pressure occupies large volumes, which would require very large facilities. Less volume is occupied if it is compressed and the volume can be further reduced by liquefaction, solidification or hydration. Therefore CO_2 can be transported in gaseous, liquid and solid state.[15] The physical state of CO_2 for transportation will mainly be defined by the energy required and the related costs. The transportation of the separated and compressed carbon dioxide is considered as a relatively mature technology compared with CO_2 capture and underground sequestration. CO_2 can be transported by pipelines, tanker trucks and ships. However, dedicated CO_2 pipelines are the most efficient transport mode for shipment.[16] After shipment of CO_2 from its source to the sink it can be stored in three different ways: Geological storage, Ocean storage and industrial fixation of CO_2 into inorganic carbonates. The geological storage allows storing of carbon dioxide in oil and gas fields,

[12] IPCC (2005, p. 3)

[13] IPCC (2005, p. 108)

[14] EEA - European Energy Agency (2008, p. 15)

[15] IPCC (2005, p. 181)

[16] World Resources Institute (2008, p. 12)

coal beds and deep saline formations, which are sedimentary rocks saturated with formation water containing high concentrations of dissolved salts. In the ocean the gas can either be directly released into the ocean water column or onto the deep sea floor.[17] Independently from the storage option applied, it has to be guaranteed that carbon dioxide is stored over the long-term without any leakage in order to avoid the release of the GHG to the atmosphere and any possible hazard to human beings due to high CO_2 concentrations, which could appear locally in case of leakage.

The following graphic shows the basic steps of the process chain in CCS systems, including the power plant as source of CO_2, the capturing and separation, compression, transport and injection of CO_2 into the storage. In the next chapter the already applied and researched technologies in the different steps within the process chain will be explained and analyzed.

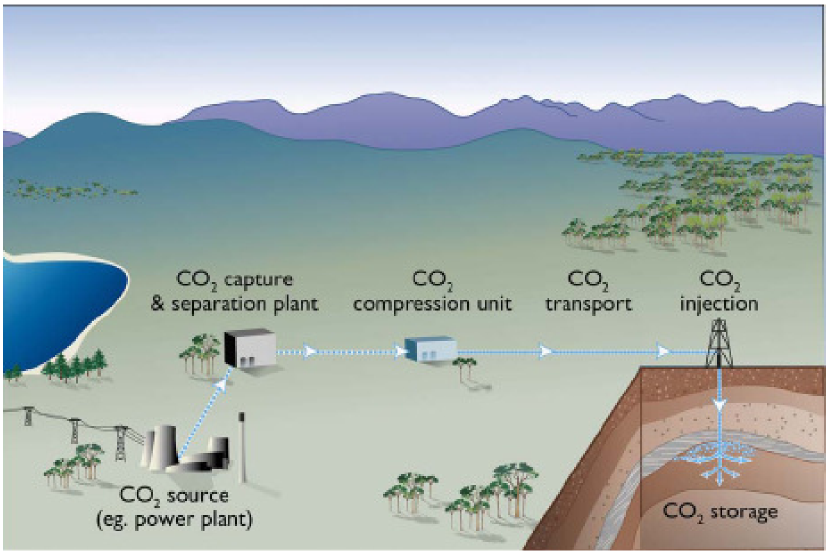

Figure 2.1: Simplified overview of CO_2 process chain from its source to the sink (Source: CRC for Greenhouse Gas Technologies (2006), Review of Geological Storage Opportunities for Carbon Capture and Storage (CCS) in Victoria, URL: http://www.co2crc.com.au/dls/pubs/regional/victoria_06_0506.pdf [10.02.2011])

2.1 Common carbon capture systems and technologies

As already mentioned above, carbon capture is likely to be applied mainly for carbon dioxide LPS within the power sector. Carbon capture technologies don´t have their origins in the power sector, already for gas- and oil reservoirs CO_2 was used to increase the oil-, respectively gas production. This process is called enhanced oil recovery (EOR) or enhanced gas recovery (EGR). In this processes

[17] IPCC (2005, p. 3)

carbon dioxide is injected into a reservoir to increase its productivity. This is also confirmed by Herzog, who speaks about the separation and capturing of CO_2 out of economic reasons, especially for EOR operations. With the decrease of the oil price in the mid-1980s EOR got too expensive and many of the capture facilities constructed in the late 1970s were forced to close.[18] Nowadays separation and capturing of carbon dioxide is as well researched and applied for the mentioned LPS within the power sector as a result out of climate change discussion. It is often considered as a major mitigation strategy.

In the following chapter the author is going to describe and discuss the existing carbon capture systems and technologies, their application and marketability (state of development). The different technical possibilities for the gas separation (separation of CO_2 from the flue gas) are called ***carbon capture technologies***. The main separation processes used for separation CO_2 from other gases are:

- Separation with sorbents/solvents
- Separation with membranes
- Distillation of liquefied gas streams and refrigerated separation

These gas separation processes can be integrated in different ***CO_2 capture systems***. At the time there are existing three main systems for carbon capture applicable for the power sector (excluding industrial processes), which are going to be described further in the following chapters:

- Pre-combustion capture
- Post-combustion capture
- Oxy-fuel combustion

2.1.1 Carbon dioxide capture technologies

Separation with sorbents/solvents

In this technology the separation of the carbon dioxide is reached by contact of the flue gas with the sorbent used. The sorbent can either be in liquid or solid state. After enriching the sorbent with CO_2, it is transported to another vessel where the CO_2 is released again (regeneration of the sorbent). This regeneration happens by heating the sorbent, decreasing the pressure or by any other change in the conditions around the sorbent. The regenerated sorbent can be recycled in the first process step to capture CO_2 again. In case of a sorbent in its solid state, there is no circulation between the vessels –

[18] Herzog (1999a, p. 1)

the regeneration is achieved by cyclic changes in pressure or temperature.[19] Due to natural losses new, fresh sorbent is needed from time to time (sorbent make-up). As mentioned before heat or pressure loss is needed for the sorbent regeneration process, which translates into required energy and therefore a decrease in the global energy efficiency. The energy demand of the process and also the sorbent material required are resulting in additional costs. Figure 2.2 illustrates the process of CO_2 capture with sorbents as described above.

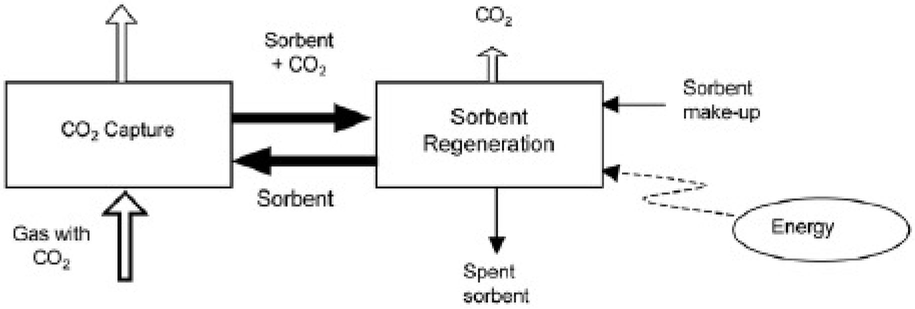

Figure 2.2: Carbon dioxide separation with sorbents/solvents (Source: Metz / Davidson a. o., IPCC, Special Report on Carbon Dioxide Capture and Storage (2005), URL: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter3.pdf, [10.02.2011])

Separation with membranes

The separation of a gas by the use of a membrane is driven by a pressure difference between the feed side (left side of the membrane in Fig. 2.3) and the permeate side (right side of the membrane in Fig. 2.3), which is also called selective permeation. Depending on the composition of the gas entering the feed side and its temperature, the type of membrane can be chosen. Common materials used are coal, ceramics, metal and polymeric membranes.[20] While the selectivity of the membrane to different gases is related to the membrane material used, the flow of gas through the membrane is driven by the pressure difference across the membrane. A high pressure difference is usually preferred for membrane based gas separation.[21] Figure 2.3 shows schematically the functionality of a gas separation process using a membrane.

[19] IPCC (2005, p. 109)

[20] Costa (2009, p. 21)

[21] IPCC (2005, p. 109)

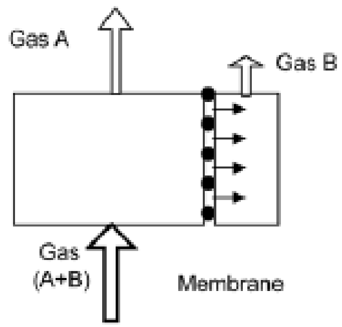

Figure 2.3: Carbon dioxide separation with membranes (Source: Metz / Davidson a. o., IPCC, Special Report on Carbon Dioxide Capture and Storage (2005), URL: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter3.pdf, [10.02.2011])

A gas mixture entering the feed side (A+B) is separated by a membrane. In case of separating carbon dioxide, either Gas A or Gas B can be the concentrated CO_2 and the other gas contains all the other remaining gas fractions.

Separation by cryogenic distillation

The separation of CO_2 by cryogenic distillation is based on a liquefaction of the flue gas due to series of compression, cooling and expansion steps. Once the flue gas is in liquid form, the different components of the gas can be separated in a distillation column. This process is commercially on large scale applied for separating oxygen from air. This technology can be applied for oxy-fuel combustion and pre-combustion capture systems.[22] The described process is illustrated below in figure 2.4.

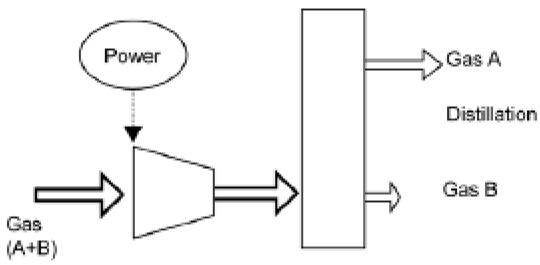

Figure 2.4: Carbon dioxide separation by cryogenic distillation (Source: Metz / Davidson a. o., IPCC, Special Report on Carbon Dioxide Capture and Storage (2005), URL: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter3.pdf, [10.02.2011])

[22] IPCC (2005, p. 110)

For the series of compression, cooling and expansion steps energy is needed to turn the flue gas into a liquid state which results in a decrease of the global energy efficiency and additional costs for the energy required.

2.1.2 Carbon dioxide capture systems

Carbon dioxide capture systems can be applied for power plants (fossil fuelled and biomass), industrial processes and in refinery processes for transforming crude oil in its final products. The main carbon capture systems existing are illustrated in the flow diagram below in figure 2.5. As the thesis concentrates on the power sector, carbon capture systems and technologies applied for industrial processes will not be described further. In post combustion capture technologies the CO_2 is removed after the combustion process from the flue gas by a CO_2 separation unit. Pre combustion capture systems use gasification systems for solid hydrocarbons to turn the solid material in a gaseous state. By using a reforming process (e.g. Steam reforming) the gaseous (or liquid) hydrocarbons can be turned into hydrogen (H_2) and carbon dioxide (CO_2). The CO_2 is captured before the combustion process and H_2 is combusted in the boiler. Oxy-fuel capture systems (or denitrogenation) are based on separating air into oxygen (O_2) and nitrogen (N_2). The hydrocarbons are combusted with pure oxygen instead of air to produce high concentrated streams of CO_2 which is capturing ready.

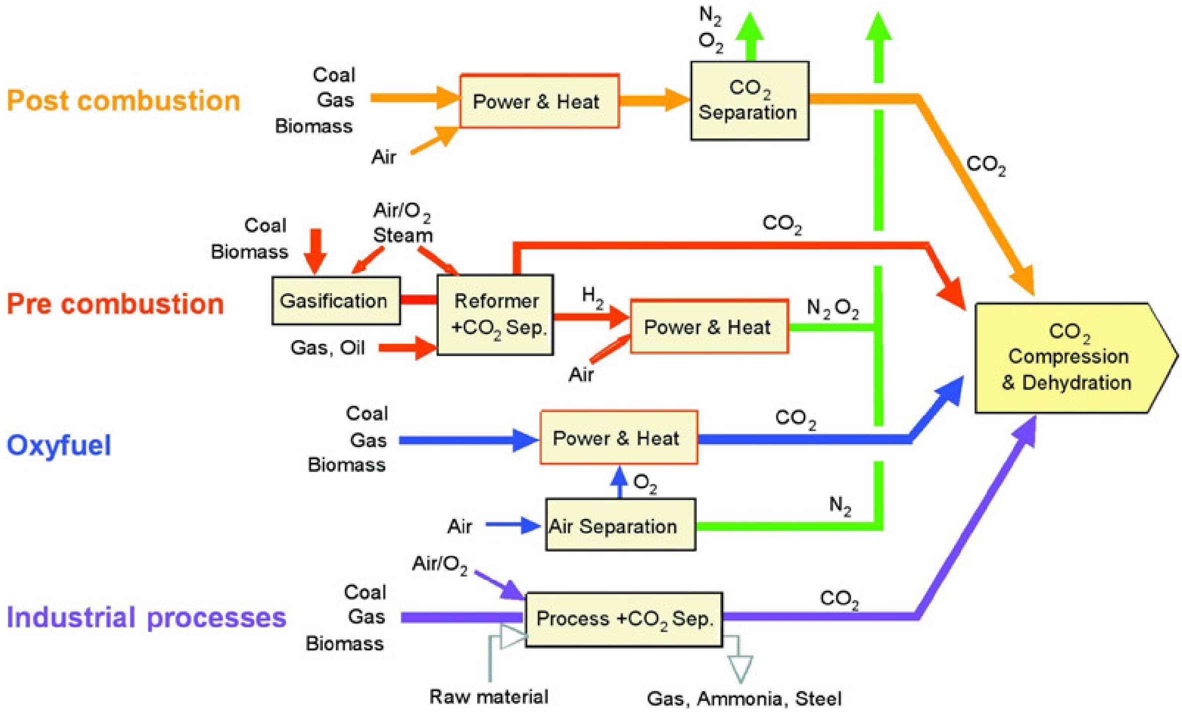

Figure 2.5: Scheme of common carbon dioxide capture systems (Source: Metz / Davidson a. o., IPCC, Special Report on Carbon Dioxide Capture and Storage (2005), URL: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter3.pdf, [04.02.2011])

The separated CO_2 has to be compressed and dehydrated to make it transportation ready. The technologies for this separation are going to be discussed further in chapter 2.2.

Depending on the capture system applied, different CO_2 capture technologies are available and applied. The following table shows the current and emerging technologies for post combustion, pre combustion and oxy-fuel capture systems.

Separation task	**Post-combustion capture (CO_2/N_2)**		**Pre-combustion capture (CO_2/H_2)**		**Oxy-fuel combustion capture (O_2/N_2)**	
Capture technology	**Current**	**Emerging**	**Current**	**Emerging**	**Current**	**Emerging**
Solvents (Absorption)	**Chemical solvents**[1]	Improved solvents Novel contacting equipment Improved design of process	**Physical solvents** **Chemical solvents**[1]	Improved chemical solvents Novel contacting equipment Improved design of processes	n. a.	Biomimetic solvents, e.g. hemoglobin derivatives
Membranes	Polymeric	Ceramic Facilitated transport Carbon Contactors	Polymeric	Ceramic Palladium Reactors Contactors	Polymeric	Ion transport membranes Facilitated transport
Solid sorbents	Zeolites Activated carbon	Carbonates Carbon based sorbents	Zeolites Activated carbon Alumins	Carbonates Hydrotalcites Silicates	Zeolites Activated carbon	Adsorbents for O_2/N_2 separation, Perovskities Oxygen chemical looping
Cryogenic	Liquefaction	Hybrid processes	Liquefaction	Hybrid processes	**Distillation**[1]	Improved distillation

[1] This carbon capture technology is the commercially and currently preferred technology for the respective capture system in most circumstances.

Table 2.1: Capture toolbox (Source: Metz / Davidson a. o., IPCC, Special Report on Carbon Dioxide Capture and Storage (2005), URL: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter3.pdf, [04.02.2011])

Post-combustion capture

Post-combustion capture is the removal of CO_2 from the power plants flue gas after the combustion process as it is also done for other pollutants such as SO_2. The removal of CO_2 is usually done by a scrubbing process which absorbs the carbon dioxide. When taking a look on the current situation of the power sector the importance of post-combustion capture systems becomes obvious. In large scale power plants fossil fuels are directly combusted with air. This results – depending on the fuel used – on large quantities of CO_2. The large presence of nitrogen from combustion air and the large scale of the power plants result in huge gas flows. As an example can be mentioned a natural gas combined cycle (NGCC) power plant having a maximum capacity of 5 million normal m³/h flue gas. The CO_2 contents of flue gases vary between 3% for NGCC and around 15% by volume for a coal-fired power plant.[23] The separation of carbon dioxide from the flue gas of the power plant in post-combustion capture systems is mainly done by using chemical solvents for the absorption process. According to the IEA, most existing CO_2 capture systems use chemical absorption in combination with heat induced CO_2 recovery (using the chemical solvent Monoethanolamine (MEA)).[24] Currently the use of chemical solvents for post-combustion capture systems offer high capture efficiency and selectivity, and the lowest energy use and costs compared to other existing capture technologies available for post-combustion capture.[25] Figure 2.6 illustrates a typical chemical carbon dioxide absorption process for power plants in a flow diagram.

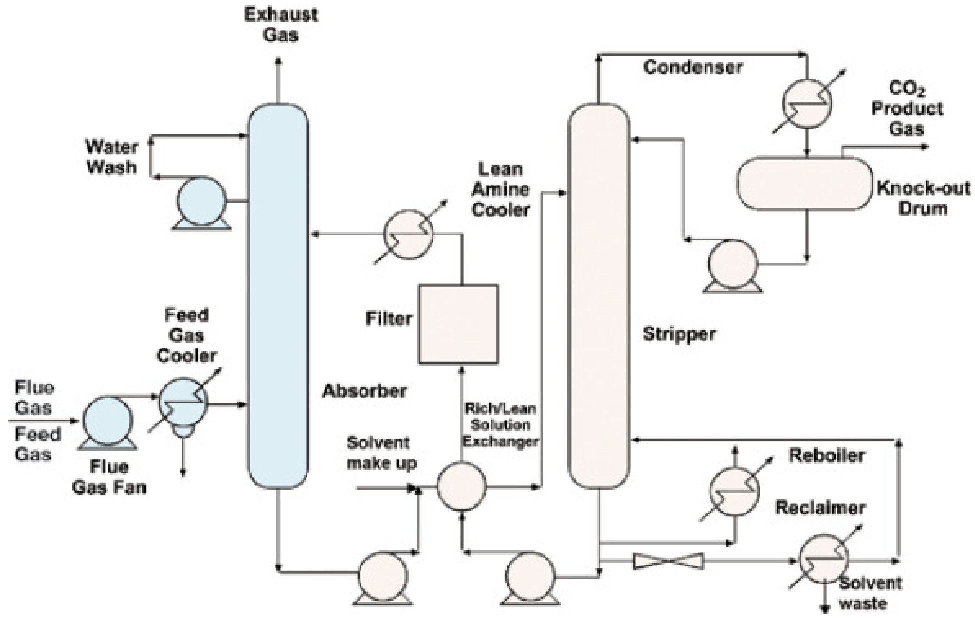

Figure 2.6: Process flow diagram of CO_2 capture from flue gas by chemical absorption (Source: Metz / Davidson a. o., IPCC, Special Report on Carbon Dioxide Capture and Storage (2005), URL: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter3.pdf, [04.02.2011])

[23] IPCC (2005, p. 114)

[24] EEA - European Energy Agency (2008, p. 48)

[25] IPCC (2005, p. 114)

First of all the flue gas is brought in contact with a chemical solvent used in the absorber (e.g. MEA), where CO_2 is bound by the solvent. This happens usually between 40 and 60°C. After the absorber a water wash section is required to balance water in the system and to remove any solvent droplets or solvent vapor carried over. As lower the remaining CO_2 concentration in the flue gas as higher the absorption vessel needs to be. The CO_2-enriched solvent is pumped to the top of a regeneration vessel (stripper), where the regeneration process of the solvent takes place at a temperature level between 100 and 140°C. For guaranteeing this temperature level in the stripper heat is supplied by the reboiler and this leads to a thermal energy penalty for the desorption process and removing the chemically bound CO_2. Furthermore steam has to be added which acts as a stripping gas. The steam is recovered in the condenser and the CO_2 product gas leaves the stripper. The recovered solvent is pumped back to the absorber vessel after passing a heat exchanger and a cooler to bring the temperature back to the level required in the absorber (40°C-60°C). [26] Before the flue gas is scrubbed of CO_2 it has to contain very low concentrations of oxides of sulphur and nitrogen (NO_2 and SO_x) as they would react with the solvent (amine) and cause a steady loss of this chemical. The required SO_x concentrations should be between 1 and 10 ppm(v). This results in an improvement of the flue gas treatment facilities for sulphur- and nitrogen oxides by using low NO_x burners with selective catalytic reduction (SCR) and using proper flue gas desulphurization facilities.[27] The key parameters determining the technical and economic operation of a post-combustion system using chemical absorption as capture technology are the following:

- Flue gas flow rate:

  Determines the size of the absorber representing a substantial contribution to the overall cost

- CO_2 content in flue gas:

  As flue gas is usually at atmospheric pressure the partial pressure of CO_2 will be around 3 to 15kPa. Aqueous amines are the most suitable absorption solvents for these conditions

- CO_2 removal:

  In practice the recovery of CO_2 is between 80% and 95%. Higher recovery rates would lead to a taller absorption column, higher energy penalties and hence to an increase of costs. The chosen recovery rate is therefore an economic trade-off.

[26] IPCC (2005, p. 115)

[27] IEA – International Energy Agency (2007a, p. 2)

- Solvent flow rate:

  With exception of the absorber the size of most equipment is determined by the solvent flow rate. Therefore the flow rate of the solvent is determined by the chosen CO_2 concentrations within the lean and the rich solutions.

- Energy requirement:

  The energy required for the process is the sum of thermal energy needed to regenerate the chemical solvent and the electrical energy consumed by the various pumps and the flue gas blower or fan.

- Cooling requirement:

  To bring the flue gas and solvent temperatures down to the required levels for an efficient absorption of CO_2 cooling is needed. Also the recovered product from the stripper requires cooling to recover the steam needed in the stripping process.[28]

At this point in time chemical solvents (amines) are mainly used for post-combustion capture due to the fact that chemical solvents are less dependent on partial pressure (partial pressure is very low for CO_2) than physical solvents. Still, chemical solvents require – compared to steam – more energy to regenerate due to the strong chemical links between carbon dioxide and the solvent.[29] Besides the commercially and currently preferred absorption technology used in post-combustion capture systems, also solid sorbents, membranes and cryogenic separation is under research and development. Studying other capture technologies aims to reduce the energy consumption and cost in the future.

Pre-combustion capture

Pre-combustion carbon capture systems can be applied for power plants using solid, gaseous or liquid combustion materials. In a first step the primary combustion material is turned into a synthesis gas (syngas) which consists out of hydrogen (H_2) and carbon monoxide (CO). The production of the syngas is based on different processes depending on the physical state of the combustion material used. For gaseous and liquid fuels “Steam reforming” (1) (water steam is added) or “Partial oxidation” (2) (oxygen is added) is used and for solid fuels (coal or biomass) a “Gasification process” can be applied. The CO fraction of the syngas is converted into CO_2 and H_2 by applying a “Water-gas shift”

[28] IPCC (2005, p. 115-116)

[29] IEA – International Energy Agency (2007a, p. 2)

reaction (3) in which steam is added. The following formulas illustrate the chemical reactions of the processes mentioned.[30]

Steam reforming

$$CxHy + H2O \leftrightarrow xCO + (x + 0.5y)H2 \qquad (1)$$

Partial oxidation

$$CxHy + \frac{x}{2}O2 \leftrightarrow xCO + \left(\frac{y}{2}\right)H2 \qquad (2)$$

Water-gas shift reaction

$$CO + H2O \leftrightarrow CO2 + H2 \qquad (3)$$

Pre-combustion capture is usually used for natural gas fired power plants in gas turbine combined cycles (GTCC) or coal based plants. When using coal and the process applied is gasification, it is known as an integrated gasification combined cycle (IGCC). The target of the gasification process is high energy efficiency and a minimum of emissions to the environment.[31] From the remaining CO_2/H_2 mixture, which has a CO_2 concentration in the range of 15-60% (dry basis) and a total pressure of 2-7 MPa, the CO_2 is removed.[32] The pressure of the gas is compared to the atmospheric pressure of the flue gas in post-combustion capture systems much higher, which allows applying other capture technologies than MEA based solvent separation. This is confirmed by Herzog, who refers to the physical solvent process (like Selexol) as much less energy intensive than the MEA separation process, because carbon capture takes place from the high pressure syngas.[33] Already table 2.1 refers to physical and chemical solvents as currently preferred separation technologies for pre-combustion capture systems.

Another separation option is the use of solid sorbents in pressure swing adsorption processes (PSA) or temperature swing adsorption (TSA). In steam reforming of natural gas and light hydrocarbons for hydrogen production, modern plants use a pressure swing adsorber (PSA). The hydrogen is separated from the other gases by adsorption in a set of switching beds contacting layers of solid adsorbents like activated carbon, alumina and zeolites. The purity of the H_2 exiting the PSA is up to 99.999%. Still,

[30] Costa (2009, p. 5-21)

[31] IEA – International Energy Agency (2007a, p. 3)

[32] IPCC (2005, p. 130)

[33] Herzog (1999b, p. 6)

PSA has not yet reached a commercial stage for separating CO_2 from flue gas.[34] Intense research and development activities on PSA for CO_2 separation show how promising this technology is considered to be in the future. Challenges lie in reducing the energy intensity of the process and to increase the CO_2 capacity for adsorbents at elevated temperatures.

When applying gasification processes for coal-fired power plants a CCGT is used to combust the cleaned syngas. The gasification is basically a partial oxidation (see reaction (2)), although steam is also supplied to the reactor in most processes.[35] Usually three different gasifiers can be used: fixed bed, fluidized bed or entrained flow gasifiers (pulverized). Before the combustion of the syngas in the turbine it has to be cleaned from impurities such as particles, tar, alkali-compounds, NH_3, H_2S, HCl and other chemical substances which can harm the installation. The condensation of tars has to be avoided in any part of the installation. Also sulfur and halogens compound abatement is an absolute necessity as the catalysts used in the installation are very sensitive to S and Cl. At present, none of the existing coal-fired IGCC plants is capturing CO_2.[36] The development of IGCC plants was initially driven by the prospects of exploiting continuing advances in gas turbine technology, the low levels of air-pollutant emissions due to the cleaned syngas, and greatly reduced process streams compared to flue gas streams at low pressure and diluted with nitrogen oxides from the combustion air in usual combustion processes. The deployment of IGCC plants is mainly restricted by the strong cost-competition with NGCC plants, the fact that they are not less costly than pulverized coal fired power plants and due to reliability concerns. [37] The decision for IGCC power plants will therefore be determined by the development of the gas/coal price ratio.

Oxyfuel combustion

In a common combustion process the primary material (coal, natural gas, biomass …) is combusted with air containing nitrogen. The high content of nitrogen in air (ca. 78% (v)) leads to the formation of nitrogen oxides (NO_X) in large quantities and therefore huge flue gas streams which complicate to capture the carbon dioxide. An approach to reduce the flue gas stream is to use pure oxygen (O_2) for the combustion process, resulting in a smaller flue gas stream which consists mainly out of CO_2 and H_2O (vapor). The oxygen used in the process has to be produced in an air separation unit, requiring

[34] IPCC (2005, p. 119/131)

[35] IPCC (2005, p. 132)

[36] IEA – International Energy Agency (2007a, p. 3)

[37] IPCC (2005, p. 133)

energy and additional installation facilities resulting in increasing costs. This is confirmed by the Department of Energy (U.S), which speaks about challenges related to the currently high capital and operating costs of Air Separation Units. These expenditures are responsible for the major part of the costs in oxyfuel combustion technology. [38] Research and development aiming to reduce the costs of oxygen production will therefore be essential to make oxyfuel combustion more attractive and competitive with pre- and post-combustion carbon capture systems. This includes steady improvements of the cryogenic distillation process, which already led to a significant cost decrease in the past 10 years and investigation efforts for alternative oxygen supply processes such as membranes.[39] Another challenge concerning oxyfuel combustion is the high combustion temperature due to the use of pure oxygen. The combustion of a fuel with pure oxygen leads to combustion temperatures of around 3500°C which is far too high for usually used power plant materials as the combustion temperature is limited to ca. 1300-1400°C for GTCC applications and ca. 1900°C in an oxyfuel coal-fired boiler considering the currently used technology. To overcome the problem of too high combustion temperatures a part of the flue gas and steam or liquid water is recycled back to the combustion chamber. The flue gas obtained from the combustion process has very high concentrations of CO_2 and contains vapor which can be cooled to condense to water in its liquid form. The IPCC refers to typical CO_2 concentrations between 80 and 98% after condensing the water vapor, depending on the fuel used and the particular oxyfuel combustion process applied.[40] Still, the NO_x content of the flue gas can not be reduced down to zero due to the nitrogen entering with the combustion material (chemical bound) and air infiltration. Furthermore the flue gas will contain mercury (Hg), unburned hydrocarbons and SO_x. Assuming that those trace species do not interfere with the sequestration process and are below certain levels, co-sequestration is possible and therefore no further controlling or scrubbing of these exhaust effluents is needed.[41] A possible co-sequestration depends on the interference with the storage side, the legal aspects of sequestrating hazardous and toxic materials (like Hg) and possible damages to installations such as pipelines (corrosion). The physical properties and chemical composition of the gas required for transportation and sequestration will be discussed further in the following chapters. Also Herzog confirms that NO_x and SO_2 tolerant sinks do not need separate control steps and NO_x and SO_2 can be sequestrated along with the CO_2, resulting in a "zero emissions" power plant.[42] The CO_2 captured by oxyfuel combustion systems is close to 100%. The International

[38] DOE/NETL (2007, p. 19)

[39] DOE/NETL (2007, p. 19)

[40] IPCC (2005, p. 122)

[41] DOE/NETL (2007, p. 18)

[42] Herzog (1999a, p. 3)

Energy Agency refers to 90-97%, which is compared to pre- and post combustion capturing systems (85-90%) significantly higher.[43] Oxyfuel combustion is at the time being at an early stage of development but integrated pilot power plants are being built and plans for commercial power plants using oxyfuel combustion are at an advanced stage.[44]

2.2 Compression and dehydration of carbon dioxide

For discussing the challenges related to the dehydration and compression of CO_2 it is necessary to describe the general physical properties of carbon dioxide. Carbon dioxide is composed by the chemical elements carbon (C) and oxygen (O) and therefore more dense than air. Very high concentrations of CO_2 can be dangerous to human beings and animals. In very small quantities it is present in our atmosphere (ca. 370ppmv)[45] and this concentration in our atmosphere is increasing. The physical state of CO_2 depends on its temperature and pressure as it is the case for any other chemical element. This variation of the physical state is illustrated below in figure 2.7 in a phase diagram.

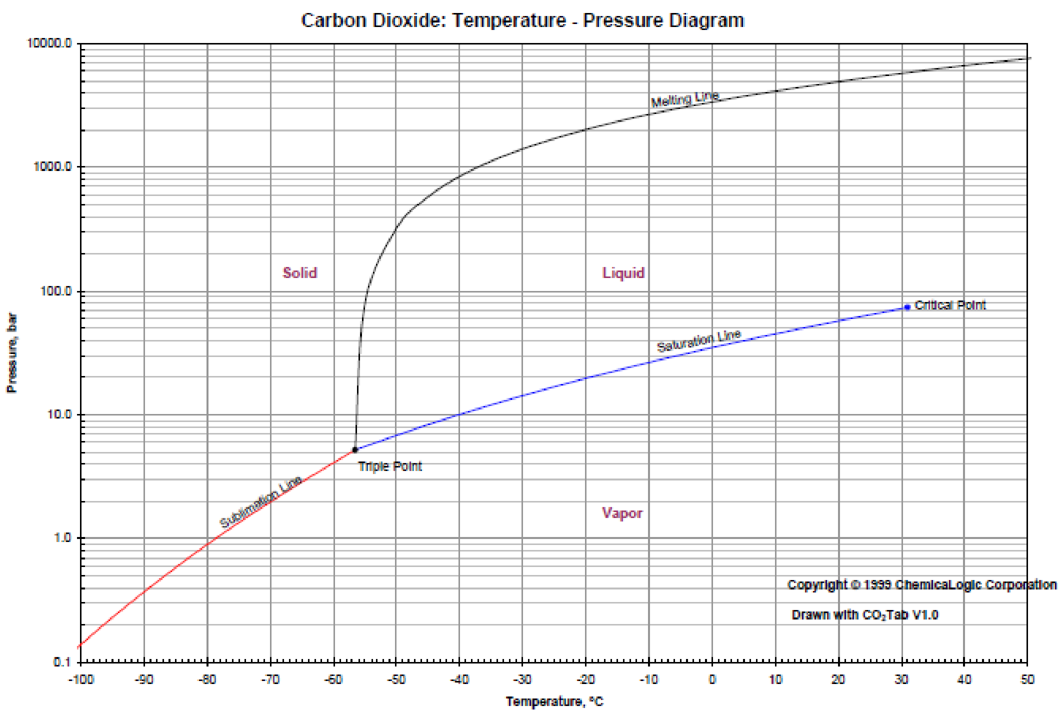

Figure 2.7: Phase diagram of carbon dioxide (Source: ChemicaLogic Corporation, 99 South Bedford Street, Suite 207, Burlington, MA 01803, USA, URL: http://www.chemicalogic.com/download/co2_phase_diagram.pdf [10.03.2011])

43 IEA – International Energy Agency (2007a, p. 8)

44 IEA – International Energy Agency (2007a, p. 4)

45 IPCC (2005, p. 385)

As observed in the diagram above CO_2 is a gas at normal temperature and pressure. At very low temperatures CO_2 can have solid state (ca. -78°C for atmospheric pressure). Taking the triple point as basis (T= -56.5°C / p=5.18bar) CO_2 can be turned into vapor (gaseous state) by decreasing its pressure and/or increasing its temperature. At a temperature between the triple point temperature (-56.5°C) and the critical point temperature (31.1°C) an increase of pressure (compression) above the saturation line will turn CO_2 into a liquid. To guarantee that the heat produced by the gas-compression doesn't exceed the critical point temperature the heat has to be removed. Temperatures above the critical point temperature at a pressure higher than the critical point pressure (73.9bar) lead to CO_2 in a supercritical state in which it behaves as a gas. This results in a very large density of carbon dioxide, approaching or even exceeding the density of liquid water. The behavior of CO_2 in supercritical state is particularly relevant for its storage.[46]

Before compressing the carbon dioxide, remaining impurities (NO_x/SO_x) and water have to be removed to avoid any damage of the transportation system (e.g. pipelines) due to corrosion and/or hydrate formation. For oxy-fuel combustion and pre-combustion capture systems cryogenic distillation columns can be used to remove NO_x and SO_x impurities. Along with the removal of SO_2 and SO_3 as sulfuric acid also almost half of the remaining H_2O content in the flue gases is removed. In a low temperature processing unit the remaining oxygen, argon and nitrogen impurities can be removed close to the carbon dioxide triple point temperature. In this cooling process two process streams are produced: capture-ready carbon dioxide and an exhaust stream consisting mostly of inert gases.[47] For CO_2 streams from post-combustion capture systems in which solvent based scrubbing processes are usually applied, the concentration of impurities is very low and many of the existing post-combustion capture plants produce high purity CO_2 for use in the food industry.[48]

To make capture-ready carbon dioxide stream after capturing from the power plant suitable for transport it has to be compressed from atmospheric pressure (ca. 1013mbar) up to a final pressure of around 150bar. At its final pressure carbon dioxide is either in liquid form or in "dense phase" regions, depending on the temperature. Somewhere between the initial and final pressure CO_2 undergoes a phase transition. In the gas phase a compressor is needed for compression, but in the liquid/dense phase the pressure can be further increased by a pump. The so called "cut-off" pressure, where the

[46] IPCC (2005, p. 385)

[47] Hong (2009, p. 11-12)

[48] IPCC (2005, p. 142))

compression process shifts from the compressor to the pump, represents the critical point pressure of CO_2 (73.9bar).[49] To compress carbon dioxide energy (electricity) is required. Typically pressurization needs around 0.22 GJ to 0.5 GJ of electricity per tone of CO_2.[50] This translates into a reduction of overall energy efficiency and results in additional costs.

2.3 Carbon dioxide transportation systems

To link the LPS of carbon dioxide with its sink a proper transportation system, depending on the transportation distance, the sink location, availability and costs, has to be found. The transportation systems under consideration in this chapter are: pipelines, ships and tanks. Also the IPCC considers in its special report about CCS these three systems as commercial-scale transport systems for liquid and gaseous carbon dioxide.[51] As already mentioned in chapter 2, carbon dioxide can either be transported in solid, liquid or gaseous state. Still, at the time carbon dioxide is mainly transported with pipeline systems as they are considered to be a mature technology and usually the most efficient one. Transportation via railway and road tankers is not explained further in this chapter as it is unlikely that they are attractive options for large-scale carbon dioxide transport from source to sink.[52]

2.3.1 Pipeline transportation systems

Pipeline based transportation of carbon dioxide is considered to be a mature technology and long-time experience makes this technology the leading technology in transporting CO_2. Worldwide already more than 2591km of pipelines transporting carbon dioxide are in operation – most of them in the U.S., where they carry 50Mt of CO_2 per year from natural sources to EOR projects in the west of Texas and elsewhere.[53] As already referred before, the concentration of impurities contained in the transported carbon dioxide can have great influence on the pipeline system due to corrosion. Therefore the concentrations of impurities need to be low enough to avoid the problem of corrosion and to ensure a long lifetime of the pipeline system used to transport CO_2 from its source to the sink. Dry carbon dioxide with a relative humidity below 60% does not corrode the carbon-manganese steels usually used for pipelines. This conclusion also applies for other impurities than H_2O - like N_2, NO_x

[49] McCollum (2006, p. 2)

[50] IEA – International Energy Agency (2008, p. 65)

[51] IPCC (2005, p. 181)

[52] IPCC (2005, p. 181)

[53] IPCC (2005, p. 181-182)

and SO_x contaminants. Especially a low-nitrogen content is required if the captured and transported CO_2 is used for EOR and a low H_2S contents for transportation of carbon dioxide through more populated areas.[54] Therefore the purity requirements for carbon dioxide are as well related to the storage side and security requirements for human beings, flora and fauna.

2.3.2 Ship transport of carbon dioxide

The second option to transport carbon dioxide is the maritime way by ship. In case that the source of carbon dioxide isn´t directly at the coastline or on riverside, also ship transport will involve pipelines as a primary transportation medium to the shore, where the carbon dioxide can be stored temporary until the ship brings it to its final destination (onshore or offshore). As many CO_2 large point sources in the power sector are close to the riverside and as they are using the river for cooling purpose, ship transport can be an option if no pipeline system is available. The IPCC refers in its special report about CCS, that CO_2 transportation by ship has a number of similarities to liquefied petroleum gas (LPG) transportation by ship and that also three types of tank structure for liquid gas transport ships (as for LPG and LNG) are used: pressure type, low-temperature type and semi-refrigerated type.[55] As mentioned before, in some cases CO_2 transportation by ship can have advantages compared to pipelines as a transport medium. This is confirmed by an IEA-study, carried out by the Mitsubishi Heavy Industries Ltd in Japan, where CO_2 transport by ship is considered to be less costly in some circumstances and that the use of some storage sides could be enabled which might not be easily accessed by pipelines.[56] However, at the time pipelines are the common mediums used to transport carbon dioxide from its source to the sink as it is always captured on land, but in some circumstances (depending on the available transportation systems, source-sink distance, location of the sink, CO_2 quantities…) transportation by ship could be the option to favor.

2.4 Carbon dioxide storage

In the following chapter the different options for long-time storage of carbon dioxide, which has been captured at LPS of the power sector and transported to the storage side, are described. For carbon dioxide a primary differentiation between the main storage possibilities has to be made: CO_2 can either be stored in underground geological storage sides, in the ocean or stored by industrial fixation.

[54] IPCC (2005, p. 181)

[55] IPCC (2005, p. 186)

[56] IEA GHG (2004, p. i)

2.4.1 Underground geological storage

The subsurface is the largest carbon reservoir of the Earth. The majority of the world´s carbon is held in coal, oil, gas and organic-rich shales and carbonate rocks. The carbon dioxide produced by biological activity, igneous activity and chemical reactions between rocks and fluids accumulates in the earths crust as carbonate minerals, in solution or in a gaseous or supercritical form, either as a gas mixture or as pure CO_2. This knowledge led to attempts of engineers to store carbon dioxide from large point sources in proper geological formations under the earth's surface. The IPCC mentions in its report that first attempts were undertaken in Texas (USA) in the early 1970s as part of enhanced oil recovery projects (EOR). [57] The geological storage options for carbon dioxide are depleted oil and gas reservoirs, EOR, deep unused saline water-saturated reservoir rocks, deep unmineable coal seams, enhanced coal bed methane recovery (ECBMR) and basalts, oil shales or cavities. These storage options are illustrated in the figure below.

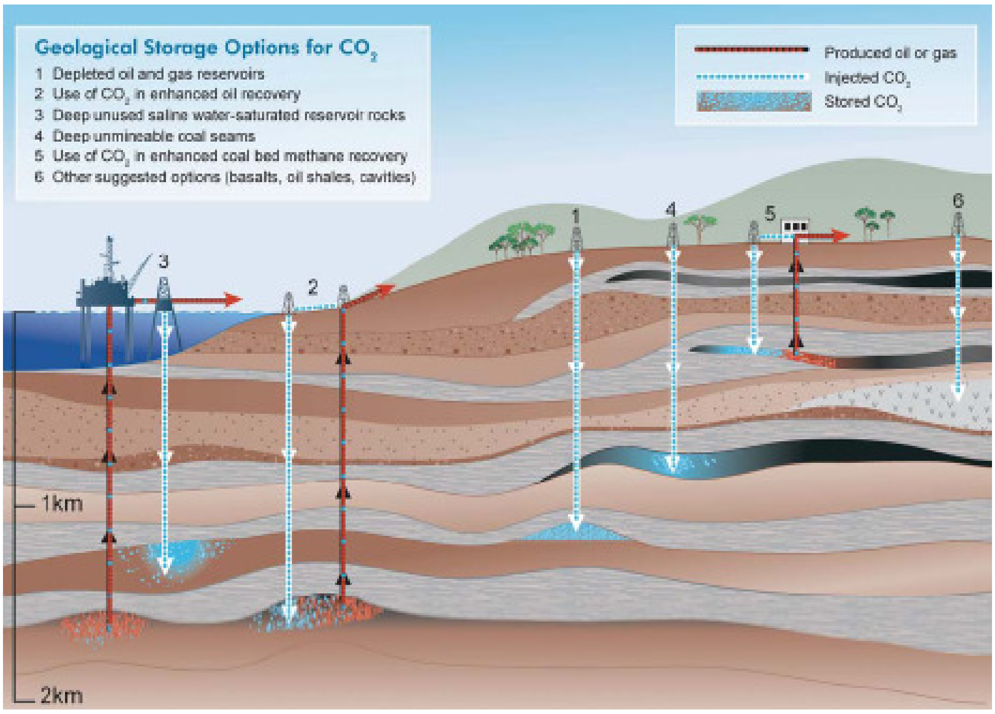

Figure 2.8: Geological Storage Options for carbon dioxide (Source: Metz / Davidson a. o., IPCC, Special Report on Carbon Dioxide Capture and Storage (2005), URL: http://www.ipcc.ch/pdf/special-reports/sroccs/srccs_chapter3.pdf, [15.03.2011])

Geological storage of CO_2 in the mentioned storage options can either be done onshore or offshore. Independently from the location of the storage side (onshore/offshore) and the available storage option, the risk of leakage has to be very low out of two main reasons: To avoid the release of CO_2

[57] IPCC (2005, p. 199)

into the atmosphere and therefore its contribution to climate change and to limit the local risk of hazards towards human beings, flora and fauna. The fraction of carbon dioxide retained in appropriately selected and managed reservoirs likely exceeds 99% of 1000 years and the risk of leakage is expected to decrease over time due to additional trapping of carbon dioxide by other mechanisms.[58] For storing carbon dioxide in sedimentary basins oil fields, depleted gas fields, deep coal seams and saline formations are available (see figure 2.8). The author is going to explain the geological storage option in deep saline formations, oil and gas fields (depleted or enhanced recovery) and coal beds (deep unmineable or enhanced recovery) further.

Deep Saline Formations

As saline formations are widespread, deep sedimentary rocks, saturated with formation waters and therefore unsuitable for human consumption or agriculture, they are a potential option to store CO_2.[59] The estimated global capacity of deep saline formations is the largest, followed by oil and gas reservoirs (depleted and enhanced recovery) and coal beds (ECBMR).[60] However, estimating the CO_2 storage capacity of deep saline formations is still a challenge nowadays. Multiple mechanisms for storage like physical trapping beneath caprock, dissolution and mineralization complicate the capacity estimation as they operate simultaneously and on different time scales. The relations and interactions between the various mechanisms are from high complexity and highly depend on local conditions. Furthermore there is no single, consistent and broadly available methodology to estimate the storage capacity and only limited seismic and well data are available as it is the case for oil and gas reservoirs.[61]

Oil and Gas fields – Depleted or Enhanced Recovery

Oil and gas fields which have been depleted and are therefore not in production anymore can be used as carbon dioxide storage sides. But also still producing fields can be used as CO_2 storage side. This processes are called enhanced oil recovery (EOR) respectively enhanced gas recovery (EGR). Injecting carbon dioxide in operating oil/gas fields serves to increase the production rate and can therefore lead to economic benefits. The IPCC confirms this conclusion in its special report about CCS

[58] IPCC (2005, p. 34)

[59] Gibson-Pole (2006, p. 5)

[60] McCoy (2008, p. 9)

[61] IPCC (2005, p. 222)

when referring to added economic benefit of incremental oil production, which may offset some of the costs of carbon dioxide capture, transport and injection due to the implementation of CO_2-EOR in areas with suitable hydrocarbon accumulations.[62] The International Energy Agency even refers to a possible compensation of the CO_2 costs by the increased oil production, when carbon dioxide is used for EOR.[63] To store CO_2 in depleted oil- or gas fields has the advantage that the risk of leakage is very low. It has been proven that the storage side is capable of storing hydrocarbons for long time periods (millions of years). Figure 2.9 illustrates the functionality of carbon dioxide based EOR.

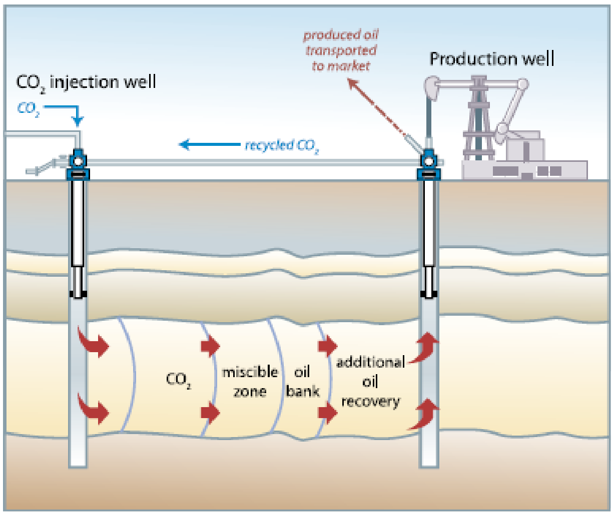

Figure 2.9: Injection of CO_2 for EOR (Source: Metz / Davidson a. o., IPCC, Special Report on Carbon Dioxide Capture and Storage (2005), URL: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter3.pdf, [16.03.2011])

Carbon dioxide is injected in an injection well and creates a miscible zone. This leads to an increased oil production due to the release of oil which has been trapped before. Some of the CO_2 is trapped in the rock formations and the rest is separated from the oil at the production well side and reinjected in the injection well. Usually 5-40% of the original oil in place can be recovered by conventional primary production. But miscible agents like CO_2 used for EOR lead to an average incremental oil recovery of 13.2% of the original oil in place.[64]

Enhanced recovery is as well possible in gas fields, although usually up to 95% of the original gas in place can be produced without EGR. Enhanced gas recovery was up to now only implemented at pilot

[62] IPCC (2005, p. 197)

[63] IEA – International Energy Agency (2007a, p. 11)

[64] IPCC (2005, p. 215)

scale.[65] Besides using carbon dioxide for enhanced recovery in gas- or oil fields, depleted oil and gas reservoirs can also be used to store CO_2. In the IPCC special report about CCS depleted oil and gas reservoirs are considered as prime candidates for CO_2 storage, as the oil and gas which is originally accumulated in traps did not escape (in some cases for many millions of years) and therefore demonstrating integrity and safety. Besides that, the geological structure and physical properties are well known and movement, displacement behavior and trapping of hydrocarbons can be predicted. Furthermore, existing infrastructure and wells may be used for handling CO_2 storage operations.[66]

Coal beds - Deep Unmineable or Enhanced Recovery

Carbon dioxide can as well be stored in deep unmineable (uneconomically) coal beds/seams or being used for enhanced coal bed methane recovery. The carbon dioxide is usually trapped by the coal due to adsorption. Also here the advantage lies in the high integrity and safety of the storage, derived from the long term storage of hydrocarbons in the reservoir. As solid coal has a very large number of micro pores, different gas molecules can easily be adsorbed. Coal has the ability to adsorb many gases and may contain up to 25 normal m^3 CH_4 (natural gas) per tone of coal at coal seam pressures.[67] In ECBMR carbon dioxide is pumped into the coal bed and the methane trapped in the coal is displaced due to the higher CO_2 adsorbtivity. The extent to which coal can adsorb CO_2 is affected by the nature of the coal (max. adsorption capacity/permeability) and the temperature and pressure of the sequestration environment.[68] ECBMR has the advantage of sequestering large quantities of carbon dioxide while increasing the production of natural gas, which results in economical benefits. Some pilot projects using carbon dioxide for enhanced coal bed methane recovery are already in operation. One of them is the Allison Unit CO_2-ECBM Pilot (USA), which started to inject CO_2 in 1995 and stopped its operation in 2001 to evaluate the results. The methane recovery increased by approximately 18%, from 77% of the original gas in place to 95%.[69]

[65] IPCC (2005, p. 216)

[66] IPCC (2005, p. 215)

[67] IPCC (2005, p. 217)

[68] Schroeder (2002, p. 55)

[69] Gibson-Pole (2006, p. 7)

3. CO_2 emissions and the power sector

To estimate the necessity for reducing CO_2 emissions within the power sector it is indispensable to name and analyze the share of CO_2 emissions of this sector on the total CO_2 emissions. Also the share of CO_2 emissions on total GHG emissions has to be analyzed. In the following chapters the author is going to analyze the anthropogenic, worldwide GHG emissions by its sector and gas. Furthermore the carbon dioxide emission data of Portugal and Spain will be discussed and stationary, large scale CO_2-emitters within the power sector identified to make a qualified statement about the possibilities and opportunities existing within the power sector of these countries to reduce their power sector related carbon dioxide emissions. The stationary, CO_2 LPS taken in consideration are the ones included in the National Allocation Plan II (NAP II) of the European Emissions Trading Scheme (EU – ETS) in the Kyoto Protocol commitment period 2008 until 2012.

3.1 Worldwide anthropogenic greenhouse gas emissions

Anthropogenic GHG emissions are directly related to human activity and have therefore a not-nature based origin. Since pre-industrial times global greenhouse gas emissions are growing, with an increase of 70% between 1970 and 2004. Also the GHG emissions due to human activities (anthropogenic origin) are increasing since pre-industrial times and have led to a marked increase in atmospheric GHG concentrations.[70] Indeed, increasing concentrations of GHGs in the earth's atmosphere enhance the greenhouse effect and result in additional warming of the Earth´s surface with all its consequences for human beings, flora and fauna. The global warming potential is different for the type of greenhouse gas. The graph below illustrated the anthropogenic greenhouse gas emissions by sector and gas in 2008, without land use, land-use change and forestry (LULUCF), for Annex I countries.

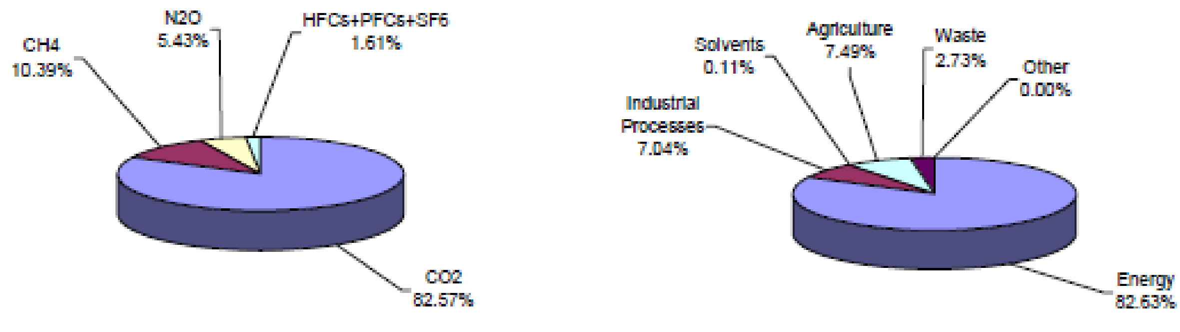

Figure 3.1: Anthropogenic GHG emissions by sector and by gas in 2008, (Source: UNFCCC, Summary of GHG Emissions for Annex I (2010), URL: http://unfccc.int/files/ghg_data/ghg_data_unfccc/ghg_profiles/application/pdf/ai_ghg_profile.pdf [20.03.2011])

[70] IPCC (2007b. p. 3)

Around 83% of the total greenhouse gas emissions in Annex I countries can be found within the energy sector and CO_2 is dominating clearly the total emissions with a share of ca. 83%. Especially the energy sector is dominated by CO_2 emissions, having a share of 94% on the total green house gas emissions related to this sector.[71] Therefore carbon dioxide emissions and energy conversion is directly connected and contribute significantly to global warming. To fulfill the global GHG reduction goal it will be essential to pay special attention on the implementation of strategies within the energy sector, including the electricity and heat production, to ensure a decoupling of energy conversion and CO_2 emissions. When taking a look on the increase of global GHG emissions between 1979 and 2004 it can be observed that the energy supply sector had the largest growth rates in this period (an increase of 145%).[72] As CO_2 has the largest share of all greenhouse gases on the total, worldwide GHG it is assumed that this is as well the case for the countries Portugal and Spain.

3.2 Carbon dioxide emissions of Portugal

In figure 3.2 the CO_2 emissions* (without Land Use, Land – Use Change and Forestry) by sector of Portugal in the year 2007 are illustrated.

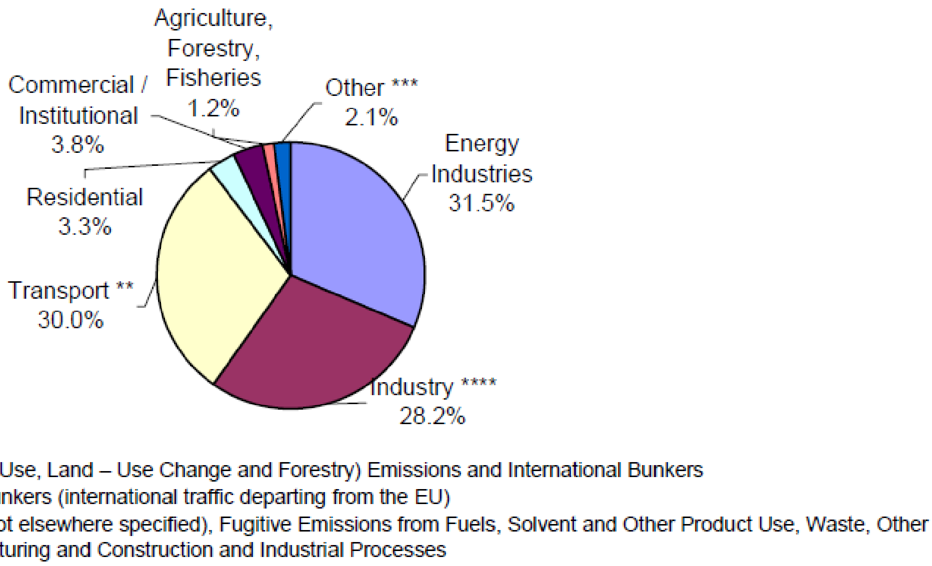

Figure 3.2: Shares of carbon dioxide emissions in 2007 by sector of Portugal (Source: European Commission, Directorate-General for Energy and Transport, EU Energy in figures 2010, CO_2 emissions by sector, URL: http://ec.europa.eu/energy/publications/doc/statistics/ext_co2_emissions_by_sector.pdf, [20.03.2011])

[71] IEA – International Energy Agency (2010a, p. 18)

[72] IPCC (2007b. p. 3)

As illustrated in the figure above, energy industries are responsible for around one third (31.5%) of the country's total CO_2 emissions. Equal shares can be found within the transportation sector (30.0%) and the industry (28.2%). These three sectors together account for 89.7% of Portugal's carbon dioxide emissions. The sector "Energy Industries" includes the subsectors "Public Electricity and Heat Production", "Petroleum Refining" and "Other Energy Industries". While the subsector "Public Electricity and Heat Production" accounts for the biggest share of emissions within the energy industry, the others only play a minor role. Due to the structure of the transportation sector (large number of relatively small CO_2 emitters), a significant reduction of emissions requires more effort than to reduce the emissions of LPS existing in the power sector and the industry (e.g. cement, steel and iron production).

3.2.1 CO_2 emissions of Portugal's power sector

When analyzing the development of carbon dioxide emissions in the past it can be observed that from 1990 until 2007 the absolute carbon dioxide emissions resulting out of "Public Electricity and Heat Production" increased from 14Mt to 17.2Mt (ca. +23%).[73] On the other hand also the total electricity generation is increasing. To make a statement about a possible decoupling of electricity generation from carbon dioxide emissions it is necessary to compare the increase in total electricity generation with the increase in the related carbon dioxide emissions. Figure 3.3 compares the total electricity generation with related carbon dioxide emissions from 1990 – 2007.

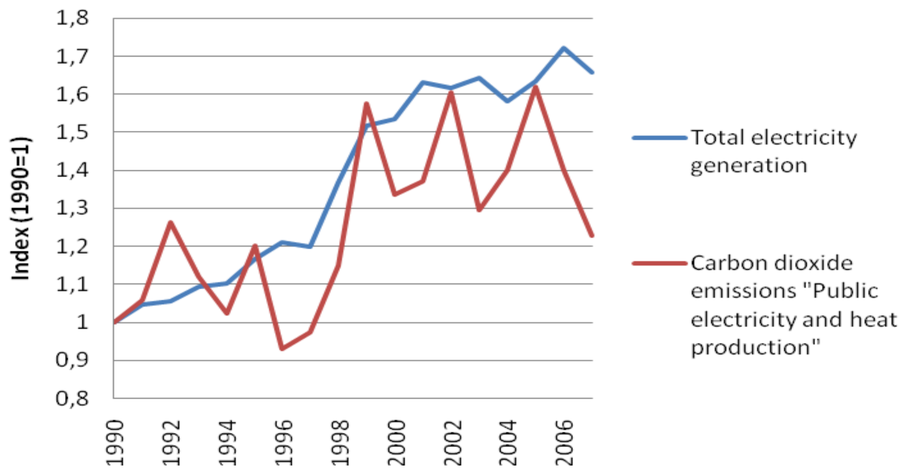

Figure 3.3: Increase in total electricity generation and related CO_2 emissions of Portugal (Data source: European Commission (2010a) and European Commission (2010b))

[73] European Commission (2010a)

The increase in carbon dioxide emissions of the sector "Public electricity and heat production" shows much more volatility than the total electricity generation, which results mainly out of the high annual variations of renewable electricity generation. In 1992 hydropower based electricity generation was significantly lower as in 1990 and 1991, resulting in an intensified use of fossil fuels, namely coal, oil and gas. In more recent years the volatility of electricity related CO_2 emissions results as well out of the electricity generation from wind farms, leading in the year 2007 to very low carbon dioxide emissions due to high electricity generation from wind farms (+128% compared to 2005) and average production from hydropower. Although a higher share of RES (renewable energy sources) in total electricity generation leads to a lower increase of carbon dioxide emissions, there is still no uncoupling of electricity generation from carbon dioxide emissions. When taking into account the mentioned CO_2 abatement objective until 2050 (-80% to - 95% compared to 1990 levels), it gets clear that only covering the annual increase of electricity generation by RES will be by far not enough to fulfill the reduction target, requiring an almost complete decarbonization of the power sector. It is necessary to reduce the carbon intensity (tCO_2/MWh) of the power sector to a minimum, resulting in huge efforts in increasing the share of RES on total electricity generation and increasing energy efficiency within the whole value chain (from production- to consumption side). Figure 3.4 illustrates the development of carbon intensity of the power sector in Portugal from 1990 to 2007.

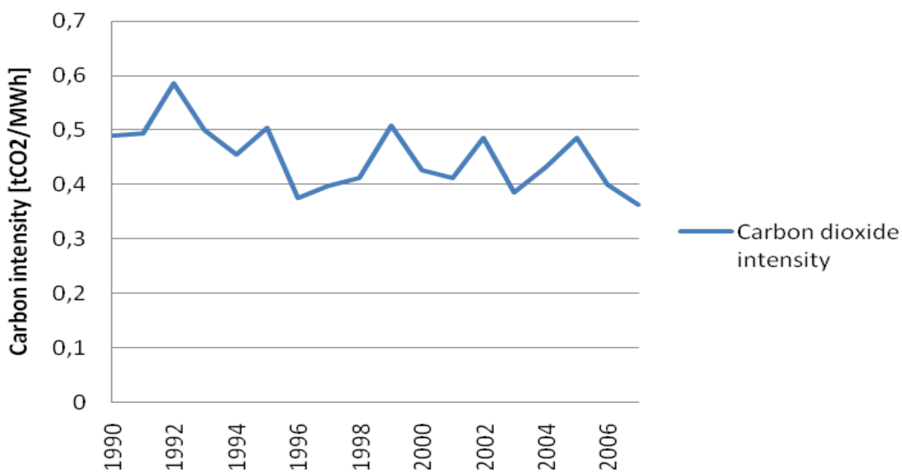

Figure 3.4: Carbon intensity of Portugal's power sector "Public electricity and heat production" (Data source: European Commission (2010a) and European Commission (2010b))

Within the last 17 years (1990-2007) the CO_2 intensity of Portugal's power sector was slightly decreasing from 490 to 360 kg of CO_2 per MWh produced, resulting out of a combination of the already mentioned increasing share of RES on electricity and heat production and efficiency improvements within this sector.

3.2.2 Identification of Portugal's stationary CO_2 LPS

The identification of Portugal's stationary carbon dioxide LPS is based on the installations included in the European Union Emissions Trading Scheme for the allocation period 2008-2012, which are defined in the National Allocation Plan (NAP II). The list of the installations and their annual emission allowances included in the NAP II (PNALE II) is illustrated in Annex I. For the second commitment period the sectors included in the EU-ETS are energy, ferrous metals, cement and lime, glass, pulp and paper and the ceramics production sector. Graph 3.5 shows the number of installations and related emission allowances per sector for the commitment period 2008-2012.

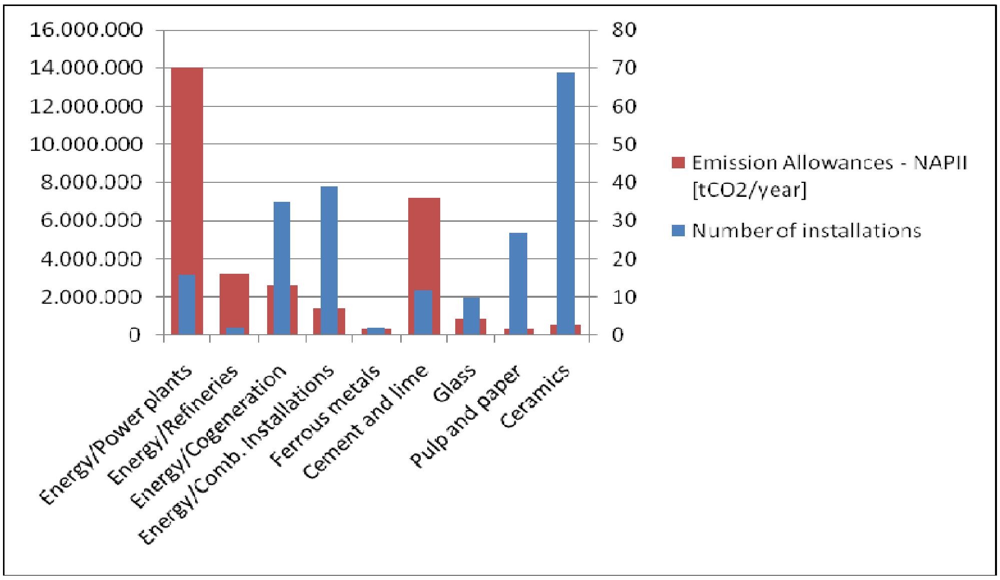

Figure 3.5: Number of installations included in the NAP II (2008-2012) of Portugal and related annual emission allowances (Data source: Plano Nacional de Alocação de Licenças de Emissão II (PNALE II) (2008b))

The total, annual emission allowances for all sectors are 34.81 $MtCO_2$, from which 30.5 $MtCO_2$ are attributed to already existing installations and the remaining 4.3 $MtCO_2$ constitute a reserve for new installations.[74] . Out of the 212 installations included in the NAP II 92 can be found within the energy sector, representing ca. 70% of the total emission allowances. Even though the category "Energy/Power plants" includes only 16 out of the total 212 installations (7.6%) of the NAP II, the emission allowances attributed to this category is close to 14 $MtCO_2$ (45.9% of 30.5 $MtCO_2$). This represents the by far the largest share of the total emission allowances, followed by the category "Cement and lime" with around 7.2 $MtCO_2$. On the other hand the sector "Ceramics" with 69 installations accounts for only 1.9% of the total annual emission allowances. A relatively large part of

[74] Plano Nacional de Alocação de Licenças de Emissão II (2008a, p. 107)

attributed emission allowances can be found in the sector “Energy/Refineries”, with only 2 installations having a share of 10.6% on the total annual emission allowances. The distribution of the emission allowances is therefore a good indicator for carbon dioxide LPS.

The identification of stationary, carbon dioxide LPS is based on the definition of the IPCC. The IPCC defines in its special report about CCS CO_2-LPS as installations with emissions of more than 0.1 $MtCO_2$ per year.[75] By applying this definition Portugal’s NAP for the period 2008-2012 includes in total 33 LPS. The distribution of these LPS over the sectors is illustrated in figure 3.6.

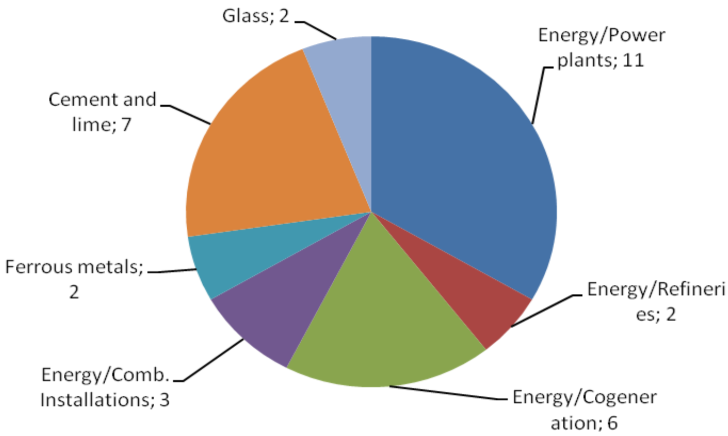

Figure 3.6: Identification of Portugal’s sectoral carbon dioxide LPS (Data source: Plano Nacional de Alocação de Licenças de Emissão II (PNALE II) (2008b))

While the sectors “Pulp and paper” and “Ceramics” have no stationary LPS, Portugal’s energy sector (Power plants, Refineries, Cogeneration and Combustion Installations) has with 22 LPS the biggest share on the total LPS. The sector “Power plants”, including the subsectors “Coal”, “Biomass”, “CCGT”, “Fuel” and “Diesel”, is with 11 LPS by far leading the ranking of sectoral carbon dioxide LPS. As the thesis is based on the analysis of a possible implementation of CCS systems in the power sector it is necessary to identify the carbon dioxide LPS of the power sector, their emission allowances and subsectors. This can help to estimate the potential of CCS systems in decarbonizing the country´s power sector in the context of the already mentioned abatement objective until 2050. Furthermore the geographical localization of the power sectors LPS will allow to estimate the distance between source and a possible sink for the captured CO_2 and the related costs of transport. Table 3.1 shows all installations of Portugal’s power sector (“Energy/Power plants” and “Energy/Cogeneration”) included in the NAP II and identifies its carbon dioxide LPS according to the definition used by the IPCC.

[75] IPCC (2005, p. 3)

Energy/Power plants	Coal	Central Termoeléctrica de Sines	5.833.317
		Central Termoeléctrica do Pego	2.723.011
	CCGT	Central Termoelétrica do Ribatejo	1.423.103
		Central de Ciclo Combinado da Tapada do Outeiro	1.198.020
	Fuel	Central Termoeléctrica de Setúbal	1.118.999
		Central Térmica da Vitória	537.383
		Central Termoeléctrica do Carregado	377.234
		Central Termoeléctrica do Caldeirão	245.432
		Central Térmica do Belo Jardim	153.040
		Central Termoeléctrica do Barreiro	138.877
		Central Termoeléctrica do Caniçal	128.328
		Central Térmica de Santa Bárbara	41.603
		Central Térmica do Porto Santo	40.036
		Central Termoeléctrica do Pico	37.773
	Diesel	Central Termoeléctrica de Tunes	4.537
	Biomass	Central Termoeléctrica de Mortágua	1.153
Energy/Cogeneration	Pulp and paper	Central de Cogeração da Soporgen	239.306
		Portucel Viana Energia	206.091
		SPCG — Sociedade Portuguesa de Cogeração Eléctrica, S. A.,	156.099
		Central de Cogeração de CACIA	98.590
		ENERPULP Lavos	85.807
		ENERPULP — Cogeração Energética de Pasta, S. A. (Setúbal)	65.832
		Caima Energia: Constância	13.476
	Chemical	REPSOL — Central Termoeléctrica	411.058
		Central de Cogeração da Energin	225.955
		Carriço Cogeração	161.539
		Bamiso	53.613
		Selenis Energia, S.A	51.079
		ENERLOUSADO — Recursos Energé ticos Lda (Continental Malboro)	42.469
	Textil	Saramagos	56.675
		SPE -Sociedade de Produção de Electricidade e Calor S. A.	46.027
		Lameirinho Recursos Energéticos S. A.	38.617
		SEVA — Central de produção combinada de calor e electricidade	29.835
		Fábrica do Arco — Recursos Energé-ticos, S. A.,	26.643
		Companhia Térmica Mundo Textil,ACE	20.938
		Companhia Térmica do Serrado, ACE	17.712
		MABERA -Acabamentos Têxteis, S. A.	13.569
		Companhia Térmica Oliveira Ferreira, ACE	11.421
	Extraction of mineral materials	Unidade de Cogeração (Adelino Duarte da Mota)	48.733
	Various	Central de Cogeração do Parque das Nações	29.259

Table 3.1: Installations of the power sector included in the NAP II and identification of LPS (Data source: Plano Nacional de Alocação de Licenças de Emissão II (PNALE II) (2008b))

The table above includes installations situated in mainland Portugal and on the islands of Madeira and Azores. Out of the 51 installations 17 are carbon dioxide LPS (grey colored fields in the table), which account for 94.6% of the total emission allowances of the sectors “Energy/Power plants” and “Energy/Cogeneration” (total emission allowances = 16.15 $MtCO_2$) and for ca. 51% of the annual emission allowances attributed to all 212 installations included in the NAP II.

3.3 Carbon dioxide emissions of Spain

In figure 3.5 the CO_2 emissions* (without Land Use, Land – Use Change and Forestry) by sector of Spain in the year 2007 are illustrated.

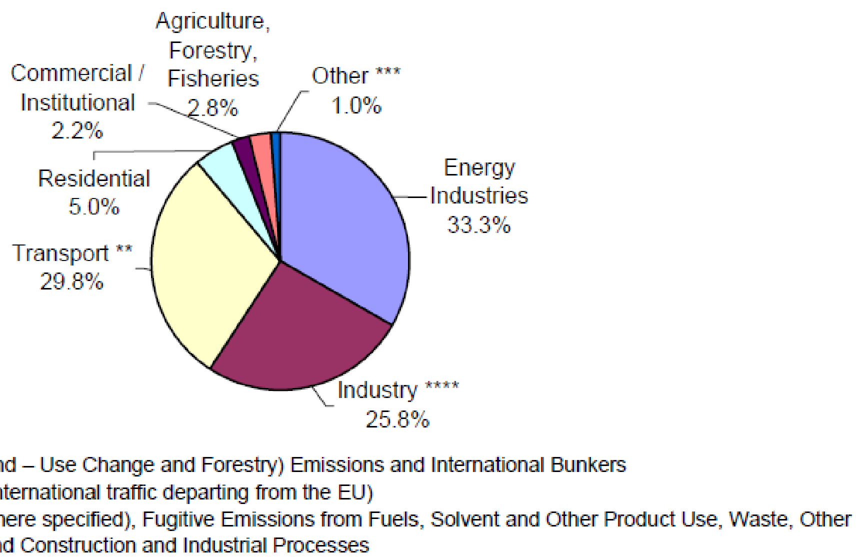

Figure 3.5: Shares of carbon dioxide emissions in 2007 by sector of Spain (Source: European Commission, Directorate-General for Energy and Transport, EU Energy in figures 2010, CO_2 emissions by sector, URL: http://ec.europa.eu/energy/publications/doc/statistics/ext_co2_emissions_by_sector.pdf, [20.03.2011])

Also Spain´s carbon dioxide emissions are dominated by the sectors “Energy Industries”, “Transport” and “Industry” with a share of 33.3%, 29.8% and 25.8% on total CO_2 emissions, respectively. Together they account for almost 90% of the country´s total carbon dioxide emissions. Dividing the sector “Energy Industries” in its subsectors shows that also in Spain “Public Electricity and Heat Production” accounts for the biggest share of emissions, resulting in a big potential to reduce its carbon dioxide emissions due to the LPS existing within this sector.

3.3.1 CO_2 emissions of Spain´s power sector

Spain´s absolute carbon dioxide emissions resulting out of "Public Electricity and Heat Production" increased between 1990 and 2007 by 67% from 64.3Mt to 107.4Mt.[76] In the same time period the country´s total electricity production almost doubled, indicating an increasing penetration of RES (mainly wind). Compared to Portugal the carbon dioxide emissions of the power sector show less volatility, also in years with high electricity generation from hydropower, due to the use of nuclear power plants, resulting in a more diversified, carbon free electricity generation. In figure 3.6 the total electricity generation is compared with the related carbon dioxide emissions, illustrating their increase from 1990 to 2007.

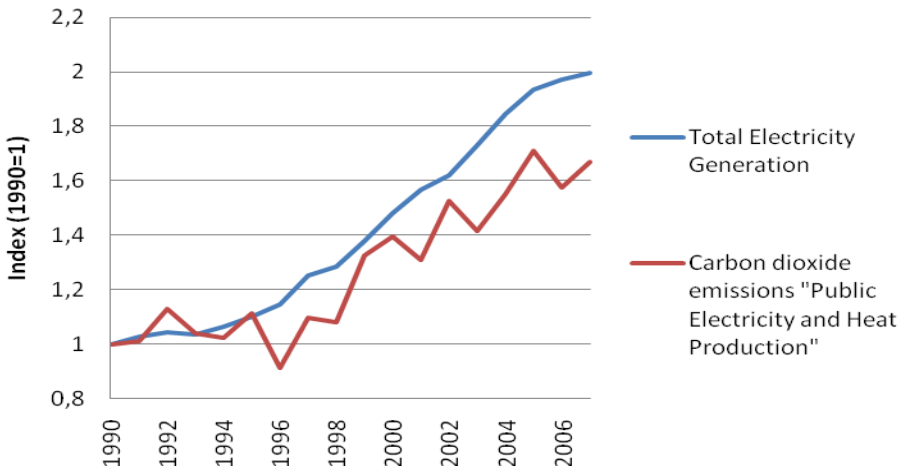

Figure 3.6: Increase in total electricity generation and related CO_2 emissions of Spain (Data source: European Commission (2010a) and European Commission (2010b))

Within the period 1990-2007 the increase in total electricity generation in Spain was sharper as the increase in carbon dioxide emissions related to the sector "Public Electricity and Heat Production", indicating a higher share of RES in the power sector and/or an intensified use of nuclear power. However, there is no uncoupling of electricity generation from carbon dioxide emissions, which would be indicated by a decrease of the sector´s CO_2 emissions. This will only happen if existing and operating fossil based power plants will be substituted by power plants based on RES. The strict CO_2 abatement objective (-80% to -95% until 2050, compared to 1990 levels) points out the necessity to uncouple the power sector from carbon dioxide emissions, requiring a sharp increase in the share of RES on total electricity generation and the already mentioned increasing energy efficiency within the whole value chain (from production- to consumption side). These measurements need to be taken to

[76] European Commission (2010a)

decrease the carbon intensity (tCO_2/MWh) of Spain´s power sector to a minimum. In figure 3.7 the development of the carbon intensity of Spain´s power sector in the period 1990-2007 is illustrated.

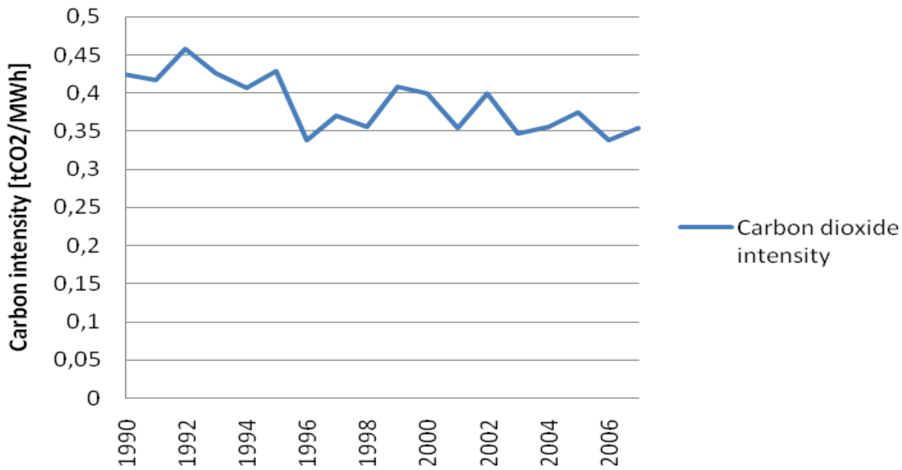

Figure 3.7: Carbon intensity of Spain´s power sector "Public electricity and heat production" (Data source: European Commission (2010a) and European Commission (2010b))

Within the last 17 years (1990-2007) the CO_2 intensity of Spain´s power sector was slightly decreasing from 424 to 354 kg of CO_2 per MWh produced, resulting mainly out of a combination of the already mentioned increasing share of RES on electricity and heat production and efficiency improvements. The GHG abatement objective of 80 to 95% for Europe set by the European Council requires an almost completely decarbonized power sector. This is as well mentioned by the European Climate Foundation, which refers in its "Roadmap 2050" to an initial analysis confirming that it is virtually impossible to achieve even the 80% GHG reduction target without a 95 to 100% decarbonized power sector.[77] The goal of a decarbonized power sector can be reached by different pathways, which include various measurements like an increasing penetration of RES, the use of nuclear power plants, improvements in energy efficiency from production to consumption side and capture and sequestration of CO_2 (CCS). These pathways and their measurements will be described and analyzed further in the following chapters. However, in the analysis of the pathways the evaluation criteria taken into account has to include the structure of today´s power sector of the country, security of supply of the power system and its reliability, the energy costs and the aspect of sustainability.

[77] ECF - European Climate Foundation (2010, p. 6)

3.3.2 Identification of Spain´s stationary CO_2 LPS

Also in the case of Spain the identification of stationary carbon dioxide LPS is based on the installations included in the European Union Emissions Trading Scheme for the allocation period 2008-2012, which are defined in the National Allocation Plan (NAP II). The sectors included in the EU-ETS are energy, ferrous metals, cement and lime, glass, pulp and paper and the ceramics production sector. As the contribution of emission allowances in the period 2008-2012 varies from year to year, the sectoral emission allowances are illustrated as annual average in the mentioned period. Graph 3.8 shows the number of installations and related emission allowances per sector for the commitment period 2008-2012.

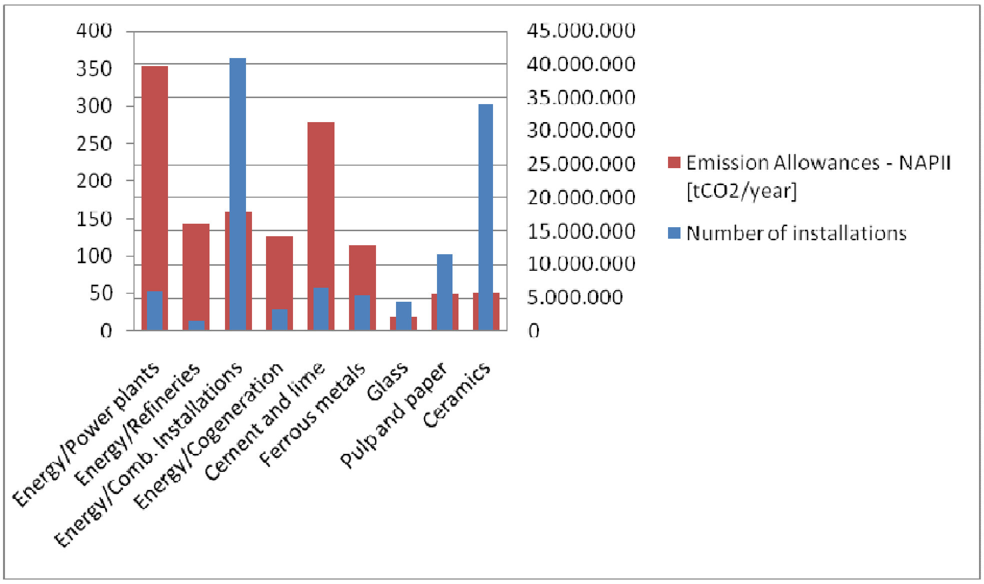

Figure 3.8: Number of installations included in the NAP II (2008-2012) of Spain and related annual emission allowances (Data source: Plano Nacional de asignación 2008-2012 (2007))

Taking into account all sectors included in the NAP II, the total, average, annual emission allowances contributed are 145.97 $MtCO_2$. In addition 6.3 MtCO2 are reserve for new installations (4.3% of the annual allocation), resulting in a total of 152.25 million tones of annual emission rights.[78] The NAP II includes in total 1008 installations and 460 can be found within the energy sector, representing around 60% of the total emission allowances. To the category “Energy/Power plants” with 54 installations (5.4%) emission allowances of around 39.8 $MtCO_2$ are contributed (27.3% of 145.97 $MtCO_2$), representing by far the largest share of the total, annual emission allowances. On the other hand the sector “Ceramics” with 301 installations (29.9%) accounts for only around 4% of the total annual emission allowances. A relatively large part of attributed emission allowances can be found in the

[78] Endesa Carbono (2011)

sector “Energy/Refineries” having with only 13 installations a share of 11.1% on the total annual emission allowances.

Also in the case of Spain the carbon dioxide LPS are identified according to the definition of the IPCC ($\geq$ 0.1 $MtCO_2$ per year), resulting in 191 LPS for the period 2008-2009. The sectoral distribution of carbon dioxide LPS in Spain is illustrated in figure 3.9.

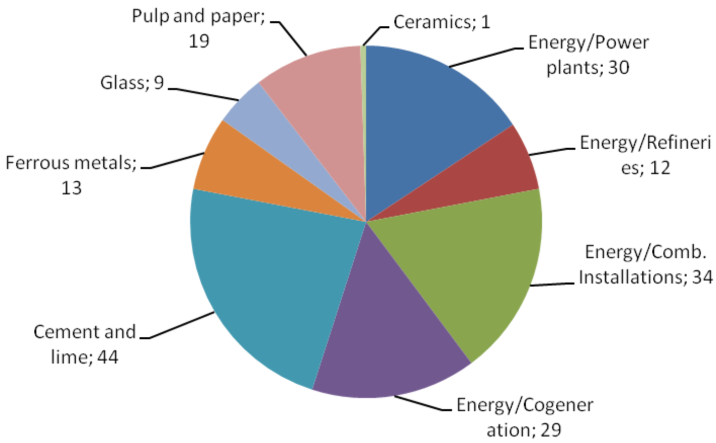

Figure 3.9: Identification of Spain’s sectoral carbon dioxide LPS (Data source: Plano Nacional de asignación 2008-2012 (2007))

Spain´s energy sector (Power plants, Refineries, Cogeneration and Combustion Installations) has with 105 LPS the biggest share on the total 191 LPS. The electricity generation sectors “Energy/Power plants” and “Energy/Cogeneration” has been awarded an average, annual emission allocation of 55.92 $MtCO_2$ for the period 2008-2012. These two sectors together include 59 carbon dioxide LPS, which have to be considered in a further source/sink analysis (estimation of the distance between source and sink and the related costs of transport). Annex II shows all carbon dioxide LPS and their related carbon dioxide emission allowances of Spain´s power sector (“Energy/Power plants” and “Energy/Cogeneration”) included in the NAP II. The carbon dioxide emission allowances illustrated are the annual average for the period 2008-2012.

3.4 CO_2 source - sink matching in Portugal and Spain

After identifying the stationary carbon dioxide large point sources of Portugal's and Spain´s power sector, potential CO_2 storage sides have to be identified to understand the geographical relationship between the sources and possible sinks. Source- sink matching is essential for assessing the potential of CCS on carbon dioxide reductions as the costs of transportation and sequestration depend on the distance between source and sink, the geological formation and transport infrastructure such as pipelines. Therefore a good source-sink matching is necessary to have low costs for carbon dioxide transport. As the IPCC mentions in its report about CCS, " if there is a good geographical relationship between the large stationary emission sources and potential geological storage sites then it is possible that a significant proportion of the emissions from these sources can be reduced using CO_2 capture and storage. If, however, they are not well matched geographically, then there will be implications for the length and size of the transmission infrastructure that is required, and this could impact significantly on the cost of CO_2 capture and storage."[79]

The identification of possible CO_2 sinks for Portugal is based on the study about CO_2 storage in deep saline aquifers of the National Institute of Engineering, Technology and Innovation (INETI – Instituto Nacional de Engenharia, Tecnologia e Inovação)[80] and the study about CO_2 sequestration in the Douro coalfield, carried out by the Fernando Pessoa University. Objective of the study about CO_2 sequestration in the Douro coalfield was to estimate the CO_2 storage capacity in a range of coal beds of different geological characteristics and to establish the feasibility of a CO_2 free industry based on carbon dioxide storage in coal seams (abandoned mines or non-mined deep seams).[81] Data source for possible carbon dioxide sinks in Spain is the research project "EU GeoCapacity – Assessing European Capacity for Geological Storage of Carbon Dioxide", in which the data required for the Europe wide adoption of CCS is provided. The project focuses on GIS mapping of CO_2 point sources, and geological storage in Europe and has as main objective to assess the capacity for geological storage of CO_2 in deep saline aquifers, oil and gas structures and coal beds. Also economic evaluations are undertaken to enable source sink matching across Europe.[82]

[79] IPCC (2005, p. 78)

[80] Machado (2007)

[81] Sousa (2007)

[82] EU GeoCapacity (2009, p. 3)

For simplification the following source-sink analysis includes only the identified LPS and possible, geological carbon dioxide sinks in mainland Portugal and Spain - sources and possible sinks at the islands of the Azores, Madeira, Canaries and Baleares are not taken into consideration. The following map illustrates all carbon dioxide large point sources of Portugal's and Spain's power sector, including the subsector "Energy/Power plants" and "Energy/Cogeneration".

Figure 3.10: Map of Portugal's and Spain´s power sector related CO_2-LPS (Data source: Plano Nacional de asignación 2008-2012 (2007) / Plano Nacional de Alocação de Licenças de Emissão II (PNALE II) (2008b))

The geographical locations of potential, geological carbon dioxide storages of Portugal and Spain (mainland) are illustrated in figure 3.11. All locations presented are based on the data of the research projects about carbon dioxide storage mentioned on the page before. More research in the area of CO_2 storage for the Iberian Peninsula would be required to obtain more information about how suitable these possible storage sides are for carbon dioxide sequestration.

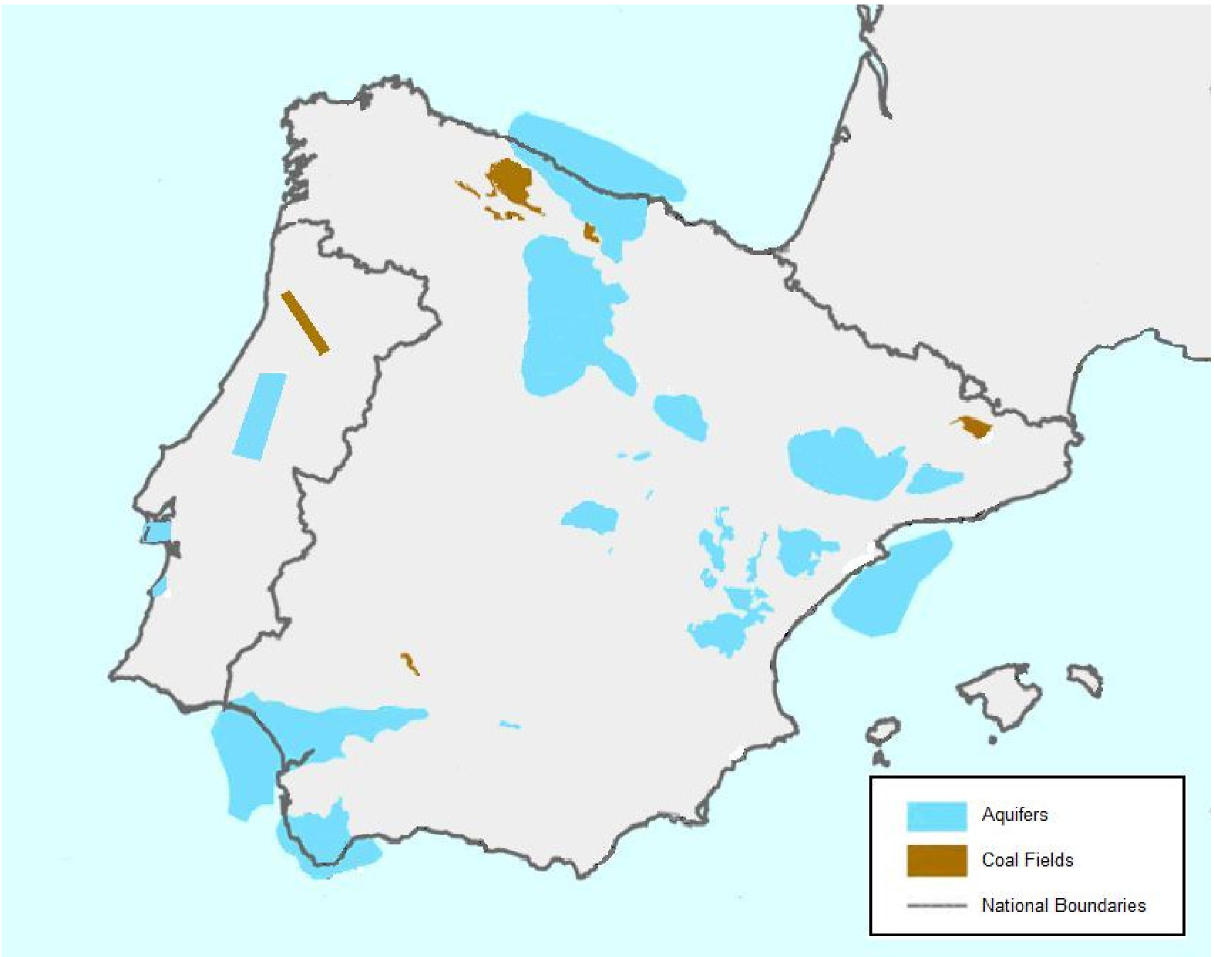

Figure 3.11: Geographical location of potential CO_2 storage sides on the Iberian Peninsula (Data source: Machado, S. / Sampaio, J. et al. (2007) / Sousa, M.L. (2007) / EU GeoCapacity (2009))

In mainland Portugal 13 CO_2-LPS were identified within the power sector and in mainland Spain 47, resulting in a total of 60 carbon dioxide large point sources for the power sector of the Iberian Peninsula. To these LPS, average annual emission allowances for the NAP II period (2008-2012) of 60.9 $MtCO_2$ are attributed (14.2 for Portugal and 46.7 for Spain). In total around 177 Mt of carbon dioxide emission allowances are attributed annually for all installations included in the NAPs for Portugal and Spain. Therefore the power sectors LPS account for around one third of the total amount of emission allowances, indicating the big potential of CCS in reducing the countries' CO_2 emissions.

When analyzing the location of the mentioned LPS, it can be observed that the main part is situated on or nearby the coastline of the Iberian Peninsula. Considering the geographical locations of CO_2 sources and sinks, it can be verified that the majority of LPS is situated within the area of potential carbon dioxide storage sides. The largest distance between CO_2 source and possible sink was found in

Spain in the region of Carboneras (Almeria), where the distance to the next sink is about 300km. In some regions there are more than one carbon dioxide LPS situated within the area of potential CO_2 storage sides (e.g. region of Andorra, Gijón, Algeciras, Huelva, Sines and the Setúbal Peninsula). Besides a good geographical matching of source and sink, the CO_2 storage capacity of the possible storage side has to be large enough for the emissions produced by the LPS over many years. When calculating the capacity of possible carbon dioxide storage sides it is important to mention that there are up to now no generally accepted standards and methodologies to calculate and even estimate the CO_2 storage capacity of a formation, structure, basin, area, country and even at worldwide level.[83] In the case of coal fields as possible storage sides, the adsorption of CO_2 in the coal is affected by a number of factors. The nature of the coal determines the extent to which that ultimate capacity will be realized. Therefore the effect of both, physical and chemical changes need to be understood and parameters such as temperature, pressure and pH might be expected to have a moderate to large influence on the adsorbtivity.[84]

However, the study “EU GeoCapacity – Assessing European Capacity for Geological Storage of Carbon Dioxide” aimed to estimate the CO_2 storage capacity in Spain. The study was carried out for aquifers, hydrocarbon fields and coal fields and lead to the following results: The storage capacity for carbon dioxide in the study´s database was estimated with 23.4 Gt in aquifers, 0.193 Gt in coal fields and the capacity in hydrocarbon fields with 0.5 Mt can be neglected, resulting in a total CO_2 storage capacity of ca. 23.6 Gt.[85] Assuming that the actual carbon dioxide emissions of the LPS equal the emission allowances attributed, that the emissions will remain on the same level and that the power stations will operate in the future, allows to compare the total storage capacity of Spain (23.6 Gt) with the emissions of the identified LPS of the power sector (46.7 Mt). Under these assumptions and not considering the economical aspects of CCS, the storage capacity in Spain is likely to be large enough to outlast the age of fossil fuel use in the power sector.

In the case of Portugal no study about the countries total carbon dioxide storage capacity could be found, but the qualification study and assessment of the CO_2 storage capacity, siting and costs in Portugal carried out for a saline aquifer situated in the west zone to the Anadia-Ferreira do Zêzere axis and Pombal Region-Ourém (Grés de Silves) assumes a storage capacity of 325 Mt. When comparing

[83] Ioakimidis (2011, p. 3092)

[84] Schroeder (2002, p. 55)

[85] EU GeoCapacity (2009, p. 107 - 111)

this value with the emission allowances attributed to all LPS and making the same assumptions as for Spain, the storage capacity of the aquifer is at least large enough to serve for more than two decades as storage side.

Only considering the geographical proximity of source and sinks, CO_2 emissions by the mentioned LPS and storage capacities is by far not enough to perform a detailed analysis of source-sink matching on the Iberian Peninsula. However, the mapping of LPS of the power sector and potential, geological CO_2 storage sides can be basis for future studies about carbon dioxide transport and storage in Portugal and Spain. Furthermore the project "COMET - Integrated Infrastructure for CO_2 Transport and Storage in the West Mediterranean" has as overall objective to "study the techno-economic feasibility of integrating carbon dioxide transport and storage infrastructures in the West Mediterranean area (Portugal, Spain and Morocco)."[86]

[86] COMET (2011)

4. Power sector of the countries researched

To analyze the different pathways to decarbonize the power sectors of Portugal and Spain in order to fulfill the GHG abatement objective set by the European Council, it is indispensable to take a look on the electricity sectors of the countries and their generation/fuel mix, to analyze the share of RES on generation and consumption and their dependency on imports.

4.1 The power sector of Portugal

4.1.1 Power sector overview

Electricity demand in Portugal has grown in the past ten years at an average annual growth rate of 4.4%, while in the same period of time GDP grew at moderate 2% per year. The gross electricity generation in 2007 was decreasing by 3.6% compared to the previous year. Prior to that, electricity demand had been rising at a higher rate than GDP growth for the past number of years (averaging 3.2% per year in the period 2003 to 2005 compared with a GDP growth rate slightly above 0.54% per year in the same period). In the period 2005 to 2007, demand growth slowed to around 2.0%. Residential and small business customers represent more than half of total consumption and the industrial sector almost 34%. In Portugal, the electricity consumption is sensitive to prevailing weather conditions, most obviously in winter. Peak demand tends to happen in December or January and a record of 9110 MW (mainland Portugal) was noted on 18 of December 2007. Consumption levels also tend to be high in July owing to very hot weather and the increasing use of cooling devices in businesses and households.[87]

Portugal's electricity generation is based on thermal power plants using coal, oil, natural gas and the use of RES, namely hydropower and lately also wind power. While a few years ago Portugal's gross electricity consumption could most of the time almost be covered by own electricity production, since around 10 years the increase in national electricity production was slowing down and gross electricity consumption was increasing as in previous years. This lead to the necessity to increase electricity imports from Spain. Also the research project "COMET" refers to quite high electricity imports in recent years resulting from higher demand and better commercial interconnections with the Spanish grid agents.[88] Figure 4.1 shows the development of total electricity generation and gross electricity consumption from 1990 until 2007.

[87] IEA – International Energy Agency (2009b, p. 107)

[88] COMET (2010a, p. 31 – 32)

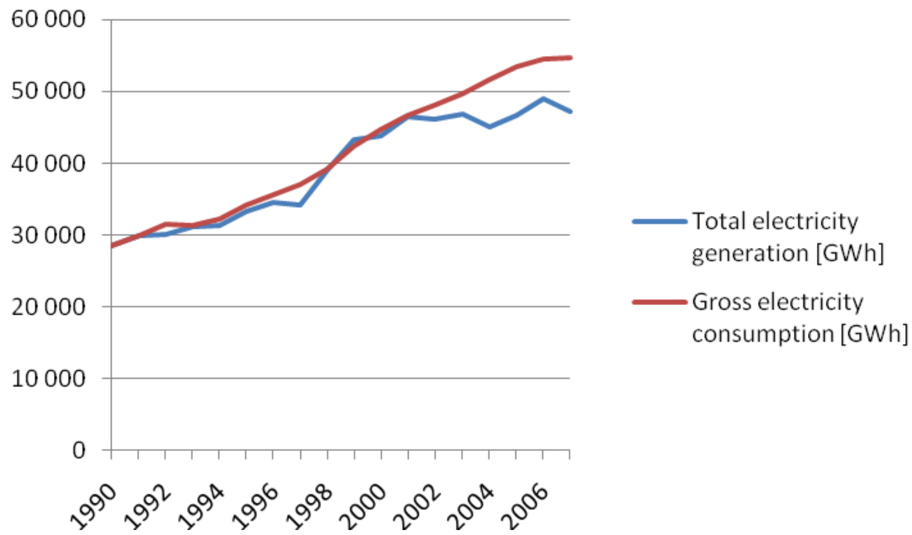

Figure 4.1: Development of electricity generation and consumption in Portugal (Data source: European Commission (2010b))

Like Portugal's electricity consumption also electricity generation is sensitive to prevailing weather conditions and very large variations can be observed in electricity generation based on hydropower. This is also confirmed by the IEA, referring to renewable power generation in Portugal (hydropower) as a highly unpredictable source that tends to depend upon local climatic conditions.[89] Annual variations of wind power based electricity generation exist, but are in amplitude and relative values lower as in the case of hydropower. This is not true when considering the extreme short term variations in wind power ramp. In years with low contribution of hydropower on total electricity production, an increasing generation out of fossil-fuel based power plants (coal, oil and natural gas) and increasing electricity imports can be observed in order to fulfill the country´s electricity demand.

Portugal has no proven reserves of oil or natural gas of any significance and at present time there is no indigenous oil- or gas production. A similar picture can be drawn for the primary energy carrier coal: Since Portugal closed its last mine in 1994, no coal has been produced. It imports coal for electricity generation especially in periods of decreased hydropower. Coal represented 10.8% of Portugal's TPES in 2008, indicating a sharp fall from the levels of the previous year. Coal consumption decreased by 12.1% mainly owing to lower coal-fired electricity production while the clinker and cement industry increased its coal use in the same period. A 17.4% decrease in total imports was recorded in 2007 compared to 2006 (3.31 Mtoe). In 2007, the total amount of imported coal was approximately 4.78 Mt,

[89] IEA – International Energy Agency (2009b, p. 135)

which includes all coal types. Portugal's main coal suppliers are Colombia and South Africa, with shares of 50.3% and 32.4% of total imports, respectively (2007 data). Other suppliers in decreasing order of importance are the US, Indonesia, Norway, Russia, Ukraine, Spain and Latvia.[90]

Out of these reasons Portugal's power sector has a high import dependency on primary energy sources (coal, natural gas and oil). The use of RES on electricity production is steadily increasing, but base load power production is still based on coal-fired power plants and the use of natural gas, which was increasing sharply within the last few years. There are two coal-fired power plants operating in Portugal. These are located in Sines (1 192 MW) and Pego (584 MW). Sines power plant, in particular, is a provider of base load power generation. Both plants operate according to the Rankine cycle with efficiencies in the range of 32% to 37%. Sines power plant has typical emissions of 890 g CO_2 per kWh.[91] Figure 4.2 illustrates the development of electricity generation mix in Portugal within the period 1990 – 2007.

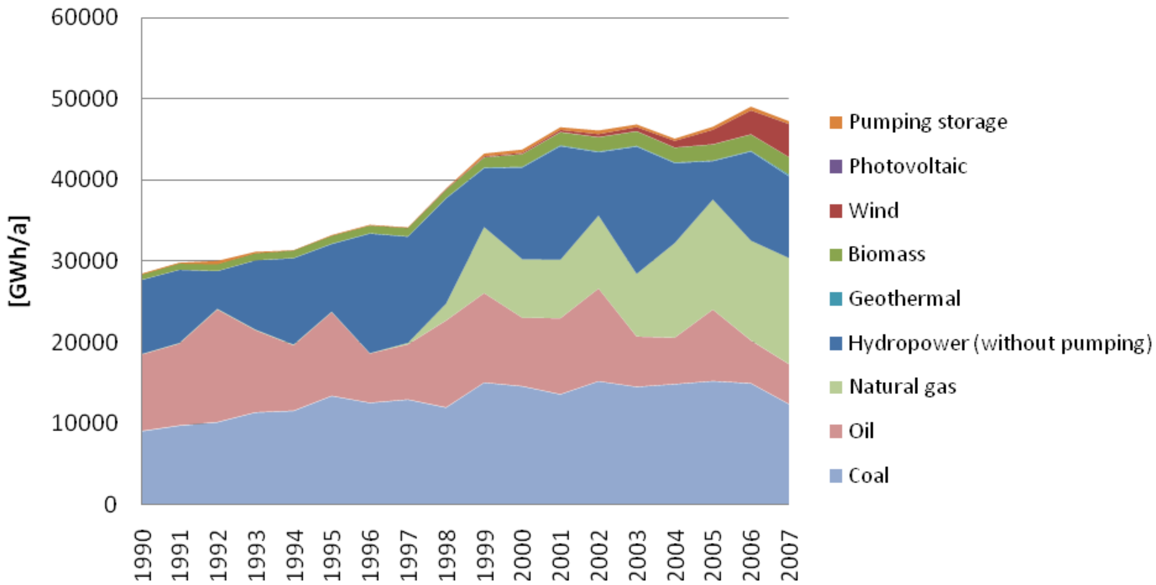

Figure 4.2: Development of Portugal's electricity generation mix in the period 1990 – 2007 (Data source: European Commission (2010b))

The graph above illustrates the decreasing share of oil-fired power plants on total electricity production and the intensified use of gas-fired power stations in years with low power production from hydropower. Besides that the intensified use of RES, mainly wind power, can be recognized.

[90] IEA – International Energy Agency (2009b, p. 67 and 80 - 81)

[91] IEA – International Energy Agency (2009b, p. 81)

It is expected that especially the electricity generation out of oil-fired power stations will face big changes in the near future. A big part of the still operating plants are or will be decommissioned, continuing the trend of a decreasing electricity production out of oil-fired power stations. Two units in the Tunes power plant in 2010 (165 MW), the Barreiro power station in 2009 (56 MW), the six units of the power plant Carregado between 2009 and 2011 (710 MW) and four groups in Setúbal in 2012 (948 MW) are already or will be decommissioned in the near future.[92] This equals a total generation capacity of 1879 MW which will be decommissioned from 2009 until 2012. The author expects that the trend of decreasing the share of oil-fired electricity generation will continue, as the highly variable fuel costs are expected to cause high uncertainty in the profitability of the power stations. This is also confirmed by the IEA, who only refers to four planned combined cycle gas turbines (CCGT) adding a further 3320 MW of capacity to the electricity system between 2008 and 2015.[93] As oil-fired power plants will be decommissioned and substituted by new generation capacity based on CCGT power plants, the trend of the last years of decreasing generation out of oil-fired power stations and increasing generation out of natural gas-fired power stations will continue in the future. In order to keep electricity import dependency on a stable level, it is necessary to substitute decommissioned power plants by new ones. Besides that it is also planned to decommission four units of the coal-fired power station in Sines in 2017 with a capacity of 1192 MW.

The total generation capacity of thermal power stations decommissioned until 2017 will be around 3069 MW. Considering the capacity decommissioned and the six new units of coal-fired power plants and nine units of CCGT planned until 2019, the country´s thermal power station´s electricity generation capacity will increase by 2859 MW net.[94]

[92] REN (2008, p. 3)

[93] IEA – International Energy Agency (2009b, p. 112)

[94] REN (2008, p. 3)

4.1.2 Renewable energy sources in Portugal's electricity generation

Renewable energy sources play an important role in Portugal's electricity generation. Especially hydropower was and is an important energy resource in the country´s electricity generation mix. Since around 10 years also the use of wind power is increasing rapidly. Between 2000 and 2007, wind power capacity in Portugal expanded exponentially from 87 MW to 2126 MW.[95] In July 2010 the capacity in operation of wind power in Portugal increased to 3852 MW (onshore), representing 22% of total installed capacity.[96] Besides wind power also the electricity generation out of biomass and photovoltaic and the use of ocean energy is increasing. However, currently hydropower is still the dominant renewable technology with 5055 MW (29%) of installed capacity followed by the non-renewable energy sources natural gas, oil and coal which together account for 43% of the total installed capacity.[97]

As graph 4.3 illustrates, the share of RES on total electricity production in Portugal was increasing significantly. The graph exemplifies the mentioned variability of electricity generation out of hydropower and the increase in electricity production from RES between 1990 and 2007.

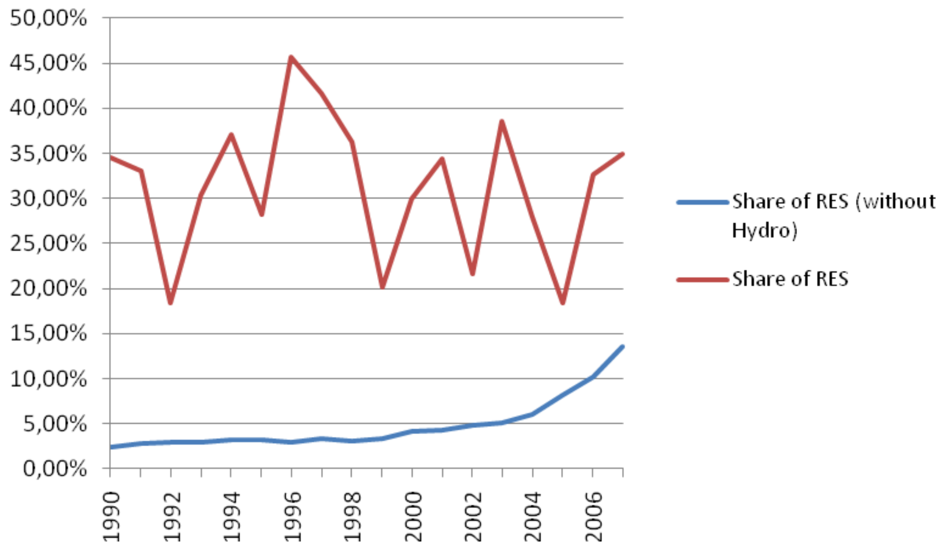

Figure 4.3: Share of RES (with and without hydropower) on Portugal's total electricity generation (Data source: European Commission (2010b))

[95] IEA – International Energy Agency (2009b, p. 135)

[96] COMET (2010a, p. 29)

[97] COMET (2010a, p. 28)

Not considering electricity generation out of hydropower, the share of RES on total electricity generation increased from 2.4 % in 1990 to 13.6 % in 2007. Main driver in this significant increase is the intensified use of wind power. To reduce the carbon dioxide emissions of the country´s power sector by around 95% by 2050 it is necessary to estimate the capacity of RES in electricity generation and their potential share on total electricity generation in 2050. The following table illustrates the primary energy endogenous technical potential of RES until 2050 in Portugal.

Resource Units	**Installed Capacity**	**Maximum Technical Potential**		
	2010	2020	2030	2050
Total Hydro GW	5,055	9,834	9,834	9,834
Hydro with pump storage GW	1,036	4,42	4,42	4,42
Wind onshore GW	3,852	6,5	7	7,5
Wind offshore (near shore B<40m) GW	0	0,5	2,50	2,5
Wind offshore (deep off-shore B<40m) GW	0	0,25	1,5	7,5
Ocean/Waves GW	0,004	5	5	7,7
PV roof panels GW	0,038	-	-	-
PV plant GW	0,081	9,3	9,3	9,3
CSP GW	0	2,4	2,4	2,4
Municipal Solid Wastes PJ	0,088 (GW)	9,83	9,99	10,43
Biogas PJ	0,02 (GW)	17,46	6,9	5,89
Conventional Geothermal GW	0,03	0,045	0,077	0,225
Geothermal (Hot Dry Rock) GW	0	0,038	0,102	0,75
Forest wood PJ Agricultural and industrial wood waste	0,47 (GW)[2]	23,08	30,87	30,87
Bio ethanol PJ	3,12% (2009P)[3]	19,50	-	-
Biodiesel PJ	3,12% (2009P)[3]	9,99	-	-

[2] Considering cogeneration
[3] Provisory value

Table 4.1: Primary energy endogenous technical potential until 2050 (Data source: COMET (2010a))

Besides the endogenous technical potential until 2050 in Portugal, it is also necessary to estimate the possible electricity generation out of RES in Portugal. The possible annual electricity generation of RES can be calculated out of the installed capacity multiplied with the expected full load hours. Uncertainties in the estimation are given as climate change for example will influence the electricity generation out of hydropower in the future, resulting in a decrease of full load hours. In this thesis the author is going to base his estimations on the study “MED-CSP - Concentrating Solar Power for the Mediterranean Region” carried out by the German Aerospace Center (DLR), Institute of Technical

Thermodynamics Section Systems Analysis and Technology Assessment. In this study the following renewable energy resources for electricity production were taken into consideration:

- Direct Solar Irradiance on Surfaces Tracking the Sun (Concentrating Solar Thermal Power Plants)
- Direct and Diffuse (Global) Solar Irradiance on a Fixed Surface tilted South according to the Latitude Angle (Photovoltaic Power)
- Wind Speed (Onshore and Offshore Wind Power Plants)
- Hydropower Potentials from Dams and River-Run-Off Plants
- Heat from Deep Hot Dry Rocks (Geothermal Power)
- Biomass from Municipal and Agricultural Waste and Wood
- Wave and Tidal Power

In the study the technical and economic potentials for each RES and country were defined. The technical potentials are in principle those which could be accessed for power generation by the present state of the art technology. For each country and RES, a performance indicator was defined, representing the average renewable energy yield with which the national potential could be exploited. As economic potentials can be understood those RES with a sufficiently high performance indicator that will allow new plants in the medium and long term to become competitive with other renewable and conventional energy sources. Their potential technical development and economies of scale are considered.[98] The following table illustrates the performance indicators used to identify the economic potentials of RES.

	Hydropower	**Geothermal**	**Biomass**	**CSP**	**Wind**	**PV**	**Tidal / Wave**
	Full Load Hours	Temperature at 5000 m Depth	Full Load Hours	Direct Normal Irradiance	Full Load Hours	Global Horizontal Irradiance	Full Load Hours
	h/y	°C	h/y	kWh/m²y	h/y	kWh/m²y	h/y
Portugal	2589	213	3500	2200	2095	1910	4000
Spain	1705	213	3500	2250	2463	2000	4000

Table 4.2: Renewable Electricity Performance Indicators, representing the average renewable electricity yield of a typical facility in each country. (Data source: MED-CSP (2005))

98 MED-CSP (2005, p. 55)

Portugal's total economic potential of RES was estimated with around 226 TWh of annual electricity production. Table 4.3 illustrates Portugal's technical and economic potential of RES in TWh per year.

	Hydropower		Geothermal		Biomass		CSP		Wind		PV		Tidal / Wave	
	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.
RES Potential [TWh]	33.0	20.0	n.a.	7.0	n.a.	26.6	436	142	63.0	20.0	n.a.	3.0	n.a.	7.0

Table 4.3: Technical and Economic Renewable Electricity Supply Side Potentials in TWh/year (Data source: MED-CSP (2005))

Assuming a baseline scenario with a linear trend in the country´s growth in electricity consumption, Portugal should have around 130 TWh of total, annual electricity consumption by 2050. Therefore the country would in theory be able to cover its total electricity consumption in 2050 by electricity generation out of endogenous RES. Even though strict energy efficiency measures are and will be applied, it is assumed that Portugal's electricity consumption in 2050 will reach the same value as in the baseline scenario. With this assumption the author applies the conclusion reached in the study "Roadmap 2050" also for Portugal and in the following as well for Spain. In the study "Roadmap 2050" decarbonized electricity consumption for Europe (including Norway and Switzerland) in 2050 is estimated to be about 4900 TWh per year, which is approximately 40% higher than today. In the baseline, the overall power demand would also grow by about 40% by 2050. However, because of growth in new sources of power demand (for electric vehicles and heat pumps in buildings and industry), the overall quantity of demand for electricity in 2050 is roughly the same as it would have been without decarbonization.[99] However, uncertainty is given due to the assumption in the baseline scenario with a linear trend of growth in electricity consumption.

[99] ECF - European Climate Foundation (2010, p. 10)

4.2 The power sector of Spain

4.2.1 Power sector overview

Also in Spain electricity demand has grown rapidly in the past years. While electricity consumption in 1990 was still around 151 TWh, in the year 2007 it reached a level of almost 298 TWh, representing an increase of ca. +97% in the mentioned period. The gross electricity generation in 2007 was ca. 303.3 TWh, making Spain to a net-electricity exporter. In 2009, Spain´s electricity net consumption reached 274.8 TWh, which represented 6.5% decrease over 2008 consumption. While in the period 2000-2005 the demand grew by 30%, from 2008 on demand shows a declining trend. It was the first time in the Spanish history that electricity consumption falls regarding the previous year.[100] This is also confirmed by the IEA, who refers to a decreasing electricity demand in the first four months of 2009, by 8.9% year-on-year. Already from 2007-2008 the increase in electricity demand was slowing down to around 1%. In Spain the largest consumer of electricity is the industrial sector having a share of around 38% on total electricity consumption. Also in Spain, the electricity consumption is sensitive to prevailing weather conditions. Summer demand typically peaks in July owing to air-conditioning load while winter demand usually peaks in December or January owing to residential heating. Annual peak demand tends to happen in winter time, with an increase of 166% from 1997 to 2007. Only in 2008 winter peak demand dropped, reflecting weak economic conditions. However, air-conditioners and electric heaters are now widespread, contributing to the rising peak demand in recent years.[101]

Spain´s electricity generation is mainly based on nuclear and thermal power plants using coal, oil, natural gas. The use of RES, mainly hydropower and wind power were contributing around 20% on total electricity generation in 2007. However, the share of RES has high annual variations due to the big variability of electricity generation out of hydropower. While in former year Spain´s electricity trade net balance was in most of the years slightly negative, Spain turned to a net exporter of electricity in recent years. Reasons for that are the increased generation out of gas-fired power stations and the sharp increase in wind power capacity. Another reason might be a slowing down economy, leading to the already mentioned decrease in electricity consumption. Figure 4.4 shows the development of total electricity generation and gross electricity consumption from 1990 until 2007 and Table 4.4 shows the international power interchanges in GWh.

[100] COMET (2010b, p. 16)

[101] IEA – International Energy Agency (2009c, p. 104-106)

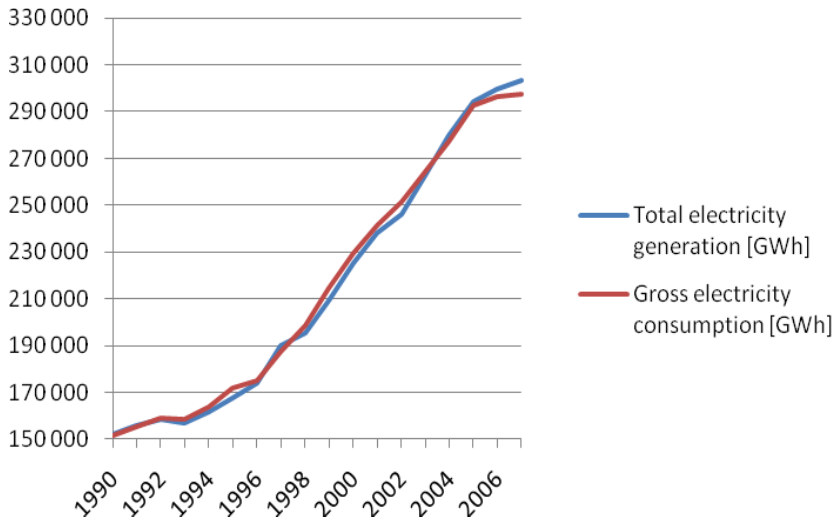

Figure 4.4: Development of electricity generation and consumption in Spain (Data source: European Commission (2010b))

	2005			2009		
	Imports	Exports	Balance	Imports	Exports	Balance
France(1)	3879	743	3136	2724	3645	-921
Portugal	706	7543	-6837	826	5617	-4791
Andorra	0	271	-271	0	301	-301
Morocco	50	834	-784	1	4591	-4590
Net balance			**-1343**			**-8104**

(1) Includes also other European countries

Table 4.4: International power interchanges in GWh (Source: REE (2010), REE (2006))

Beside Spain´s electricity consumption also electricity generation is sensitive to prevailing weather conditions and large variations can be observed in electricity generation based on hydropower. In years with low contribution of hydropower on total electricity production, an increasing generation out of fossil-fuel based power plants can be observed in order to fulfill the country´s electricity demand. Especially the share of gas-fired power stations on electricity production is increasing significantly. The year 2005 was characterized by very low electricity generation out of hydropower (-38% compared to 2004), resulting in a larger contribution of gas-fired power plants (+ 41% compared to 2004).

Spain has very scarce fossil fuel reserves. Domestic oil production is negligible and in 2008, 99.8% of all oil was imported. The imports came from more than 20 countries. Russia had the largest share (15%), followed by Mexico (13%), Iran (12%), Saudi Arabia (11%), Libya (10%) and Nigeria (9%).[102] After oil, natural gas is the second most important fuel in Spain, providing 25.3% of TPES in 2008.

[102] IEA – International Energy Agency (2009c, p. 51)

Spain is one of the fastest growing gas markets in Europe. Alone from 2007 to 2008 supply increased by 9.6%. Spain´s domestic gas production is negligible, as imports have a share of more than 99% on national gas needs. The major part of gas imports in 2008 came from Algeria (32%), followed by Nigeria (20%), Qatar (13%), Trinidad and Tobago (12%), Egypt (11%) and Norway (7%). Power generation alone was consuming around 42% of all gas in 2008 and demand growth is driven by the power sector which more than doubled its gas use from 2001 to 2008.[103]

Also the primary energy carrier coal mainly has to be imported. In 2007 imports accounted for 73% of coal supplies and domestic production for the remaining 27%. National coal (apart from lignite) is subsidised and as subsidies are being gradually reduced, production is declining. In the period 1990 – 2007, Spain´s domestic coal production decreased by 53% to 17.2 Mt (5.5 Mtoe). Currently around 90% of coal is used in the power sector to generate electricity and the remaining 10% for industrial processes, mostly iron, steel and cement industry.[104] Like gas-fired power stations, also coal based electricity generation varies annually according to hydrological conditions. In the year 2007 coal provided around 73 TWh of electricity, representing 24% of total electricity generation. According to the IEA, these figures dropped significantly in 2008, when coal accounted for only 15% of total generation. In recent years it can be recognized that the competition with natural gas based power generation is increasing. This is due to the fact, that carbon dioxide emissions per unit of electricity generated (kgCO_2/MWh) for coal is higher as for natural gas. Coal-fired power plants in Spain have a efficiency of 36% to 37% and have specific CO_2 emissions of 930 kgCO_2/MWh, whereas CCGTs have an efficiency of ca. 52% and 365 kgCO_2/MWh. Assuming a functioning market for carbon dioxide in the EU-ETS, the variable costs of coal-fired power plants are more increasing than the ones for gas-fired power plants. Depending on the gas/coal price ratio, the merit order of generation can change. The IEA confirms that Spain’s merit order is largely defined by the relative prices of coal, natural gas and CO_2 allowances in a competitive market.[105] The influence of the price for CO_2 allowances and the gas/coal price ratio on the merit order and related consequences for the power sector will be discussed further in the following chapters.

Out of the mentioned reasons Spain’s power sector has a high import dependency on primary energy sources (coal, natural gas and oil). The use of RES on electricity production is steadily increasing, but

[103] IEA – International Energy Agency (2009c, p. 61)

[104] IEA – International Energy Agency (2009c, p. 77)

[105] IEA – International Energy Agency (2009c, p. 78)

base load power production is still based nuclear power, coal-fired power plants and the use of natural gas, which was increasing sharply within the last few years. Figure 4.5 illustrates the development of electricity generation mix in Spain within the period 1990 – 2007.

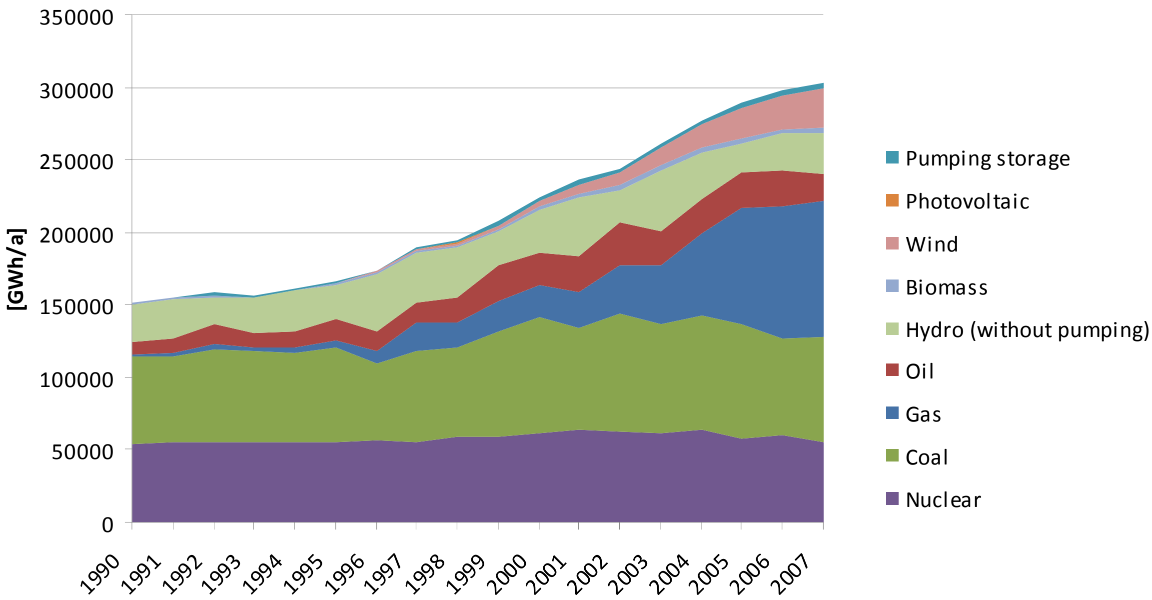

Figure 4.5: Development of Spain's electricity generation mix in the period 1990 – 2007 (Data source: European Commission (2010b))

The graph above illustrates the increasing share of natural gas-fired power plants on total electricity production and the variability of hydropower production. Besides that the intensified use of RES, mainly wind power, can be recognized. It is expected that the mentioned competition between gas-fired and coal-fired power stations will continue in the future. After the NAP II period, which will end in 2013, it is expected that the price for carbon dioxide emissions allowances will increase, as no emission rights are allocated anymore. In a competitive market, in which price is determined by offer and demand, the variable costs for coal-fired power stations will increase. This can lead to a shift in the merit order of Spain´s electricity generation, favoring the use of gas-fired power stations. In Spain, the market-driven process of investment in generation led to the commissioning of numerous new combined-cycle power plants. Massive investment in CCGT and wind technology shifted coal fired plants to the end of the merit order, allowing Spain to increase its power production while simultaneously reducing CO_2 emissions.[106] The fact that subsidies for domestic coal production are being gradually reduced, leads to higher import dependency for this primary energy carrier and will also influence the role of coal-fired power stations in the future.

[106] Wagner (2009, p. 8)

4.2.2 Renewable energy sources in Spain´s electricity generation

Also in Spain renewable energy sources play an important role in electricity generation. Where in former times renewable electricity generation was mainly coming out of hydropower, electricity generation out of wind power was increasing sharply. In 2007, electricity generation out of wind power was about the same as out of hydropower (ca. 27.5 TWh). Between 2000 and 2007, wind power capacity in Spain expanded almost exponentially from 2206 MW to 15095 MW.[107] While in 2007 wind power based electricity generation was around 27.5 TWh, this value increased to 32.5 TWh in 2008 and to 37.2 TWh in 2009. Therefore in recent years wind power became the dominant RES in Spain’s power sector with 15721 MW of installed capacity in 2008, representing around 17% of total installed power generation capacity in Spain and 10% of the country´s annual electricity generation.[108] Besides wind power also the electricity generation out of biomass and photovoltaic is increasing. Especially large growth rates can be observed in the photovoltaic sector, which increased its electricity generation significantly since 2005.

As graph 4.3 illustrates, the share of RES on total electricity production in Spain was increasing significantly. The graph exemplifies the mentioned variability of electricity generation out of hydropower and the increase in electricity production from RES between 1990 and 2007.

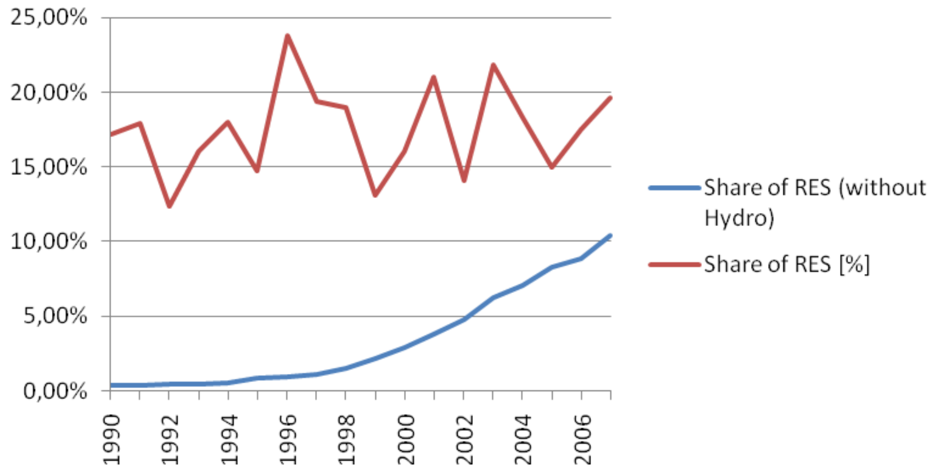

Figure 4.6: Share of RES (with and without hydropower) on Spain´s total electricity generation (Data source: European Commission (2010b))

[107] IEA – International Energy Agency (2009c, p. 93)

[108] Gobierno de España (2009, p. 47) / IEA – International Energy Agency (2009c, p. 106)

Not considering electricity generation out of hydropower, the share of RES on total electricity generation increased from 0.4 % in 1990 to 10.4 % in 2007. Main driver in this significant increase is the intensified use of wind power. To reduce the carbon dioxide emissions of the country´s power sector by around 95% by 2050 it is necessary to estimate the capacity of RES in electricity generation and their potential share on total electricity generation in 2050. The following table illustrates the technical and economic potential of the different RES in Spain in TWh. Spain´s total economic potential of RES was estimated with around 1517.5 TWh of annual electricity production, representing around 5 times the electricity consumption in Spain in 2007. The highest potential technology is attributed to solar power (CSP and PV) followed by biomass and wind power.

	Hydropower		**Geothermal**		**Biomass**		**CSP**		**Wind**		**PV**		**Tidal / Wave**	
	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.
RES Potential [TWh]	70.0	41.0	n.a.	9.4	n.a.	111.1	1646	1278	226.0	60.0	n.a.	5.0	n.a.	13.0

Table 4.5: Technical and Economic Renewable Electricity Supply Side Potentials in TWh/year (Data source: MED-CSP (2005))

Assuming a baseline scenario with a linear trend in the country´s growth in electricity consumption, Portugal should have around 750 TWh of total, annual electricity consumption by 2050. Therefore the country would in theory be able to cover its total electricity consumption in 2050 by electricity generation out of endogenous RES. Even though strict energy efficiency measures are and will be applied, it is assumed that Spain´s electricity consumption in 2050 will reach the same value as in the baseline scenario. As in the analysis of Portugal's power sector in the previous chapter, the author applies the conclusion reached in the study "Roadmap 2050", where power consumption in 2050 is estimated to be about the same as in the baseline scenario. However, making this assumption for Spain´s power sector, uncertainty is given due to the assumption in the baseline scenario with a linear trend of growth in electricity consumption. Furthermore it is difficult to estimate the technical and economic potential of RES and large variations can be found in the literature. In the description of the Spanish energy system and policies analysis in the project "COMET", Spain´s technical potential of the different renewable technologies is estimated with 496 to 3438 TWh per year.[109]

[109] COMET (2010b, p. 19)

Besides the mentioned uncertainty, it is questionable if 100% RES on total electricity generation is technically feasible and the best pathway out of an economical perspective. A high share of RES on electricity generation requires higher transmission grid capacities to ensure that renewable sources like wind power and solar power can be utilized when they are available. The induction of so called "smart grids" and demand side management measures will minimize additional required transmission grid capacities and the need for highly flexible backup generation capacities. Furthermore it is more reasonable to implement CCS technologies in countries where there is a high penetration of fossil-based, large-scale power plants within the energy sector as well as it is more likely that countries with large carbon dioxide storage opportunities are inducing this technology. The penetration of CCS technologies within a country will therefore strongly depend on the structure of energy supply in terms of how carbonized the country is and on the availability of sufficient opportunities for storing the sequestrated carbon dioxide. This is confirmed by Vallentin who mentions that CCS is more likely applied in high carbonized regions and that the dimension of CCS diffusion is determined by a country´s geological condition.[110] However, carbon dioxide emissions of Portugal's and Spain´s power sector will need to be reduced drastically (as already mentioned by around 95%). The IEA refers in its study "Energy Technology Perspectives 2010- Scenarios & Strategies to 2050" to carbon dioxide Baseline emissions (i.e. business as usual) of 57Gt. [111] This means that CO_2 emissions will double from 2010 to 2050, if no deep reduction in CO_2 emissions will take place.

[110] Vallentin (2007, p. 3)

[111] IEA – International Energy Agency (2010b, p. 47)

5. Induction of CCS technologies within the power sector

The required reduction of carbon dioxide emissions within the power sector´s of the countries Portugal and Spain by 95% until 2050 lead to an increasing demand for RES. Besides increasing significantly the share of RES on electricity generation investment in CCS technologies offers the chance for a more diversified generation mix while CO_2 emissions can be reduced at the same time. In the following chapter the author will analyze the role of RES and CCS within the power sector in the context of a carbon dioxide emissions reduction by 95% until 2050. Two different decarbonized pathways within the power sectors of Portugal and Spain will be studied and analyzed on a technical and economical scale. These pathways differ in their shares of a mix of renewable energy technologies, CCS technologies for fossil fuels (coal and gas) and, in the case of Spain, nuclear energy. The analysis of the pathways is based on the study “Roadmap 2050”, in which “business as usual” growth in electricity demand is avoided almost completely by applying aggressive energy efficiency measures. As already described in previous chapters, because of growth in new sources of power demand (for electric vehicles and heat pumps in buildings and industry), the overall quantity of demand for electricity in 2050 is roughly the same as it would have been without decarbonization. In the pathways analyzed, electricity imports from neighbor countries and breakthroughs of future technologies are not necessary. The pathways are based on technologies that are commercially available or in late-stage development today. Mentioned breakthroughs in technology will only improve the cost and feasibility of the pathways.[112]

5.1 CCS technologies in Portugal’s power sector

The share of the different RES for electricity generation considered in the analysis of the pathways, are based on the economic renewable electricity supply side potentials in TWh/year as illustrated in the previous chapters. As electricity imports are not necessary for the scenarios analyzed, a baseline scenario with a linear trend in the country´s growth in electricity consumption is assumed. According to this linear trend, Portugal should have around 130 TWh of total, annual electricity consumption by 2050. Therefore electricity consumption by 2050 will be covered by indigenous electricity generation. However, an exact estimation for the countries electricity consumption by 2050 is not necessary. When electricity generation is not completely covered in 2050 by own production units, the opportunity of electricity imports from neighbor countries (e.g. Spain and Morocco) is still an option, as long the electricity imported is produced out of RES. Huge potential for renewable electricity generation (solar power) is attributed to Portugal’s neighbor countries. For example, the DESERTEC

[112] ECF – European Climate Foundation (2010, p. 6)

Foundation has as objective to be able to meet a considerable part of the increasing electricity demand of MENA countries (Middle East and North Africa) and, in addition to that, to cover about 15% of Europe´s energy demand with clean power from deserts by the year 2050.[113]

The share of the different renewable energy sources on the country´s electricity generation in 2050 is derived from total economic potential of RES. In one scenario, the share of RES on electricity production is determined with 60% by 2050 and the remaining 40% are covered in even shares by conventional electricity production out of coal- and gas fired power stations, using CCS technologies. The second scenario assumes 80% electricity generation out of RES by 2050 and 20% out of CCS based coal- and gas-fired power stations in even shares. Furthermore the extent to which the economic potential of the RES will be used (Max. use [%]), is in principle limited with 50%. Those sources which are already today used in a higher extend are only limited by the historical highest value of annual electricity produced by this RES. As the highest economic potential is attributed to CSP (Concentrating Solar Power), the remaining electricity needed to cover 60% (respectively 80%) of the country´s electricity generation by RES will be covered by this electricity generation technology. Table 5.1 illustrates the extent to which the different RES in Portugal will be used in the 60% RES scenario and their annual electricity generation in TWh by 2050. Furthermore their share on total electricity generation by 2050 is shown.

	Hydro power	Geo	Biomass	CSP	Wind	PV	Tidal / Wave	Total
Econ. Potential [TWh]	20	7	26.6	142	20	3	7	225.6
Max. use [%]	80	50	50	17	80	50	50	
Generation [TWh]	16	3.5	13.3	24.1	16	1.5	3.5	77.9
Share [%]	12.3	2.7	10.2	18.6	12.3	1.2	2.7	60

Table 5.1: Max. use of RES by 2050 and their annual electricity generation under the 60% RES scenario (Data source: MED-CSP (2005))

In the case of hydro power the max. use was limited to 80% of the economic potential, due to the fact the electricity generation out of this RES reached already in 2003 around 15.7 TWh. Furthermore it is expected that the use of wind power will increase in the near future. In 2010 electricity generation out of wind power was about 9 TWh, representing ca. 45% of the country´s economic potential for this

[113] DESERTEC (2011)

RES.[114] AS for hydro power the author assumes in the scenario analysis a max. use of 80% of the economic potential. This means that wind power based electricity generation will have to double until 2050. Electricity generation out of geothermal sources in 2007 was around 0.2 TWh and has to reach about 3.5 TWh by 2050. Also biomass based electricity generation has to increase by the factor 6 to reach 13.3 TWh in 2050. The remaining need for RES based electricity generation by 2050 will mainly be covered by CSP plants, reaching a total electricity generation of ca. 24 TWh in 2050. The development of this technology will play a key-role in the countries electricity generation by 2050, as the use of the other RES available is limited by their economic potential which is summed up lower than the economic potential of CSP. When solar electricity generation technologies (mainly CSP) will not be used in the extend as in the scenario analysis, electricity generation out of other RES or conventional power plants with CCS technology will have to increase to fulfill the countries CO_2 reduction target by 2050.

The max. use of each RES is defined in the previous table and is the same in the 60% and 80% RES scenario. Only the max. use of CSP electricity generation is increased from 17% in the 60% RES scenario to 34% in the 80% RES scenario. The following table shows the share of the different electricity generation technologies on total electricity generation by 2050 in each pathway.

			Coal	Coal CCS	Gas/Oil	Gas CCS	Wind	Solar	Biomass	Geo-Thermal	Hydro	Tidal/Wave
2007	RES*	36%										
47 TWh	Coal/Gas/Oil	64%	26	0	38	0	9	0	5	0	22	0
2050	RES*	60%										
130 TWh	CCS	40%	0	20	0	20	12	20	10	3	12	3
2050	RES*	80%										
130 TWh	CCS	20%	0	10	0	10	12	40	10	3	12	3

*** Not including "Pumping storage" and "Others"**

Table 5.2: Share of different electricity generation technologies by 2050 in percent of total electricity generation (60% RES and 80% RES scenario)

The share of fossil fuel fired power stations on total electricity generation has to be reduced until 2050 from 64% (2007) to 40% in the 60% RES scenario and 20% in the 80% RES scenario. This results in a massive reduction of carbon dioxide emissions for Portugal's power sector. The reduction of CO_2 emissions is mainly limited by the carbon dioxide capture efficiency of the gas- and coal-fired power

[114] COMET (2010a, p. 29)

plants. According to the IPCC, current commercial CO_2 capture systems can reduce CO_2 emissions by 80-90% kWh^{-1} (85-95% capture efficiency).[115] When analyzing the reduction of CO_2 emissions within the power sector under the two different scenarios, the author will consider an average capture efficiency of 90%. As total electricity generation in 2050 is assumed to be around 130 TWh, 26 TWh have to be produced by gas-fired and coal-fired power stations (52 TWh in total) in the 60% RES scenario. For calculating the CO_2 emissions of the power plants in the decarbonized pathways it is necessary to estimate the specific emissions of coal- and gas-fired power stations. The specific CO_2 emissions ($kgCO_2$/MWh) depend on the efficiency of the power stations and the fuels used and vary therefore from country to country. However, it is considered that specific carbon dioxide emissions of gas- and coal fired power plants are the same in Portugal and Spain. According to the International Energy Agency, the carbon dioxide emissions per MWh of electricity generated in Spain are 930 kg/MWh for coal-fired power stations and 365 kg/MWh for gas-fired power stations.[116] These values are also applied for Portugal's power sector. The following table illustrates the carbon dioxide emissions of Portugal's power sector by 2050 in the 60% RES scenario. In this scenario the remaining 40% of national electricity generation are covered in even shares by coal- and gas-fired power stations, each of them contributing with 26 TWh on national, annual electricity generation.

			Specific CO_2 Emissions [kg/MWh]	Emissions without CCS [Mt]	Capture Efficiency	Emissions with CCS [Mt]	Reduction (compared to 1990)
20% Coal CCS	26	TWh	930	24.2	90%	2.4	
20% Gas CCS	26	TWh	365	9.5	90%	0.9	
				33.7		**3.4**	**76.0%**

Table 5.3: Reduction of carbon dioxide emissions by CCS technologies in the 60% RES scenario

In the 60% RES for Portugal's power sector, the carbon dioxide emissions would decrease drastically compared to the linear baseline scenario without CCS. If by 2050 52 TWh (2x26 TWh) of electricity would be generated by coal- and gas-fired power plants, the annual carbon dioxide emissions would be around 33,7 Mt. Taking into account the carbon dioxide emissions of the subsector "Public Electricity and Heat Production" in 1990 (14 Mt), this would mean an increase of ca. +141%. Inducing CCS technologies for gas- and coal-fired power stations with a capture efficiency of 90%, results in a reduction of these emissions from 33,7 Mt to 3,4 Mt. Compared to 1990 levels this signifies to a reduction of ca. 76%. However, in order to reach the ambitious target of limiting climate change to an

[115] IPCC (2005, p .107)

[116] IEA – International Energy Agency (2009c, p. 78)

increase of temperature by max. +2°C, the European Union formulated the target of reducing GHG emissions by -50% by 2050 compared to 1990 on a global level. For the power sector this translates in an almost complete decarbonization (-95%), setting the maximum carbon dioxide emissions of Portugal's power sector by 2050 at 0.7 Mt. The calculated carbon dioxide emissions in the 60% RES scenario will almost be 5 times higher. The calculation before is based on a few assumptions which lead to high uncertainties in the result. Out of the following reasons it is expected that carbon dioxide emissions in Portugal can be reduced by 95% by 2050:

- Portugal's national energy strategy aims to cover 60% of the electricity produced in 2020 by RES.[117] This likely translates into higher a share of RES on national electricity generation by 2050, making the 80% RES scenario for 2050 more plausible.
- The author expects that the increase in electricity consumption/generation will slow down and not follow the linear baseline scenario assumed before. This results in less electricity generated also by gas- and coal-fired power plants. Policy trend shows in this direction, as Portugal's national target is to reduce final energy consumption by 20% by 2020.
- Currently the considered values for specific carbon dioxide emissions for coal-fired power plants are above the European average of 0.881 kg CO_2/kWh.[118] It is expected that specific CO_2 emissions will probably decrease in the future due to efficiency improvements, helping to increase the reduction of CO_2 emissions per unit of electricity generated (kg CO_2/kWh) and therefore increasing the emission reduction.
- Carbon dioxide emissions of Portugal's power sector show big annual variations due to the high share of hydroelectric power plants. Electricity generation out of hydropower depends on fluctuations in annual precipitation. It is questionable if the baseline year 1990 is representative for averaged hydropower production.

In the 80% RES scenario, in which only 20% of national electricity generation has to be covered by gas- and coal-fired power plants using CO_2 capture technologies, it is possible to reduce the carbon dioxide emissions by 88.4% (the EU-average of 0.881 kg CO_2/kWh for coal-fired power plants is considered). Limiting in addition the average annual increase in electricity generation to 0.8%, the country´s total electricity generation will reach ca. 76 TWh in 2050, resulting in a carbon dioxide emission reduction of ca. 93.2%. Even though this represents a rough estimation, the increase in electricity generation (76 TWh by 2050) follows the results of the study "Roadmap 2050". In this

[117] Zorrinho (2010, p. 8)

[118] Dubios (2008, p. 8)

study the increase in power consumption for Europe was estimated with +42.03% (from 3450 TWh in 2005 to 4900 TWh in 2050). Assuming the same increase within the same period for Portugal this results in a power consumption of 75.85 TWh in 2050. However, absolute necessities to reach the ambitious goal of reducing CO_2 emissions in Portugal's power sector by 95% (in which national consumption equals national generation) are:

- Having a share of 80% of RES in national electricity generation.
- To limit average increase in electricity consumption to 0.8% per year (76 TWh by 2050), which requires strict measurements in energy efficiency improvements over the whole value chain.
- Improving the efficiency of coal- and gas-fired power plants to decrease the specific carbon dioxide emissions (kg CO_2/kWh) below EU average.
- To apply CCS technologies in all existing conventional, fossil fuel fired power plants. Not capturing CO_2 from gas-fired power plants would limit the reduction of carbon dioxide emissions to 80%.

5.2 CCS technologies in Spain´s power sector

According to the baseline scenario with a linear trend in the country´s growth in electricity consumption, Spain should have around 750 TWh of total, annual electricity consumption by 2050. Also in the case of Spain the assumption is made, that by 2050 the country will cover its total electricity consumption by indigenous electricity generation. If electricity generation is not completely covered in 2050 by own production units, opportunities to import electricity from neighbor countries (e.g. Spain and Morocco) is still an option, as long the electricity imported is produced out of RES.

The share of the different renewable energy sources on the country´s electricity generation in 2050 is derived from total economic potential of RES as illustrated in the previous chapter. In one scenario, the share of RES on electricity production is determined with 60% by 2050 and the remaining 40% are covered by nuclear power plants (10%) and conventional electricity production out of coal- and gas fired power stations, using CCS technologies in even shares of 15%. The second scenario assumes 80% electricity generation out of RES by 2050, 10% out of nuclear power plants and 10% out of CCS based coal- and gas-fired power stations in even shares. Also for Spain the extent to which the economic potential of the RES will be used (Max. use [%]), is in principle limited with 50% and RES which are already today used in a higher extend are only limited by the historical highest value of annual electricity produced by this RES. As the highest economic potential is attributed to CSP

(Concentrating Solar Power), the remaining electricity needed to cover 60% (respectively 80%) of the country´s electricity generation by RES will be covered by this electricity generation technology. Table 5.1 illustrates the extent to which the different RES in Portugal will be used in the 60% RES scenario, their annual electricity generation in TWh by 2050 and their share on total electricity generation by 2050.

	Hydro power	Geo	Biomass	CSP	Wind	PV	Tidal / Wave	Total
Econ. Potential [TWh]	41	9.4	111.1	1278	60	5	13	1517.5
Max. use [%]	100	50	50	23	80	50	50	
Generation [TWh]	41.0	4.7	55.6	293.9	48.0	2.5	6.5	452.2
Share [%]	5.5	0.6	7.4	39.2	6.4	0.3	0.9	60

*** Not including "Pumping storage" and "Others"**

Table 5.4: Max. use of RES by 2050 and their annual electricity generation under the 60% RES scenario (Data source: MED-CSP (2005))

For hydro power the max. use of its economic potential was defined with 100%. This results out of the high electricity generation by this RES in previous years, which reached already in 2003 around 41 TWh. The max. use defined for wind power (80%) results out of the existing wind park electricity generation, which contributed already in 2007 with 27.5 TWh on total electricity generation. In 2009 this value increased to 37.2 TWh, which represents around 62% of the total economic potential for wind power in Spain.[119] It is expected that the use of wind power will increase further in the near future. Until 2050 wind power based electricity generation will have to increase by +29% to reach the required 48 TWh of annual electricity generation (considering wind power production in 2009). Up to now electricity generation out of geothermal sources does in fact not exist. By 2050 the country´s potential has to be used in an extent to reach at least 4.7 TWh of annual electricity generation. Biomass based electricity generation has to increase by the factor 15 to reach 55.6 TWh in 2050. The remaining need for RES based electricity generation by 2050 will mainly be based on solar power plants, namely CSP plants, reaching a total annual electricity generation of ca. 293.9 TWh in 2050. In 2007 solar power based electricity generation reached only 0.501 TWh, representing ca. 0.2% of the country´s total electricity generation. Therefore the development of this technology will play a key-role in the countries electricity generation by 2050, as the use of the other RES available is limited by their economic potential which is summed up 5 times lower than the economic potential of CSP. In case that solar electricity generation technologies (mainly CSP) will not be used in the extend as

[119] Gobierno de España (2009, p. 46)

considered in the scenario analysis, electricity generation by conventional power plants with CCS technology will have to increase to fulfill the countries CO_2 reduction target by 2050. Even if the economic potential of all other RES would be used in full extent (max. use of 100%), they could only cover 32% of the country´s total electricity generation. As consequence import dependency for fossil fuels would increase drastically compared to the 60% and 80% RES scenario.

The following table shows the share of the different electricity generation technologies on total electricity generation by 2050 in each pathway (60% RES and 80% RES). While the max. use of wind-, solar-, biomass-, geothermal-, hydro- and tidal/wave-based electricity production are the same in the 60% and 80% RES scenario, the extent to which solar power based electricity generation is used in the generation portfolio is increased from 39.5% in the 60% RES scenario to 59.5% in the 80% RES scenario.

			Coal	Coal CCS	Gas/ Oil	Gas CCS	Nuclear	Wind	Solar	Bio mass	Geo	Hydro	Tidal/ Wave
2007	RES*	20%											
300 TWh	Coal/Gas/Oil	62%											
	Nuclear	18%	24.5	0	37.5	0	18.5	9	0	1	0	9.5	0
2050	RES*	60%											
750 TWh	CCS	30%											
	Nuclear	10%	0	15	0	15	10	6.5	39.5	7.5	0.5	5.5	1
2050	RES*	80%											
750 TWh	CCS	10%											
	Nuclear	10%	0	5	0	5	10	6.5	59.5	7.5	0.5	5.5	1

Table 5.5: Share of different electricity generation technologies by 2050 in percent of total electricity generation (60% RES and 80% RES scenario)

The share of fossil fuel fired power stations on total electricity generation has to be reduced until 2050 from 62% (2007) to 30% in the 60% RES scenario and 10% in the 80% RES scenario. The remaining 10% are covered by nuclear power plants, requiring an additional generation capacity of ca. 19.5 TWh (ca. + 35%) by 2050. It remains to be seen how the actual discussion about nuclear power plants in the electricity generation portfolio will influence the decision for new generation capacities in Spain. However, less generation capacities of nuclear power plants will require additional capacities of RES in order to reach the same reduction in CO_2 emissions as with an intensified use of nuclear power plants. According to Spanish regulation, the operating nuclear units can remain in service as long as the Nuclear Safety Council (Consejo de Seguridad Nuclear, CSN) remains favorable to their being in operation. Current policy of the government follows the strategy to reduce the share of nuclear power in the energy mix progressively.[120] Considering the actual discussion in Europe about the future of nuclear power, initiated by the nuclear accident in Japan in 2011, it is expected that Spain will at least follow this policy in the future. This makes, at the time being, a decision for new nuclear power generation capacities in the near future unrealistic.

For analyzing the reduction of CO_2 emissions in the two pathways the author will consider an average capture efficiency of 90%. Electricity generation by 2050 in Spain is assumed to be around 750 TWh. Therefore around 112.5 TWh have to be produced by gas-fired and coal-fired power stations (225 TWh in total). As for Portugal, also for Spain the specific CO_2 emissions ($kgCO_2/MWh$) are assumed to be 930 kg/MWh for coal-fired power stations and 365 kg/MWh for gas-fired power stations (average values in 2009). In the following table the carbon dioxide emissions of Spain´s power sector by 2050 in the 60% RES scenario are illustrated. The 60% RES scenario assumes that 30% of national electricity generation is covered in even shares by coal- and gas-fired power stations, each of them contributing with 112.5 TWh on national, annual electricity generation and the remaining 10% by nuclear power stations (75 TWh).

			Specific CO_2 Emissions [kg/kWh]	Emissions without CCS [Mt]	Capture Efficiency	Emissions with CCS [Mt]	Reduction (compared to 1990)
15% Coal CCS	112.5	TWh	0.930	104.6	90%	10.5	
15% Gas CCS	112.5	TWh	0.365	41.1	90%	4.1	
				145.7		**14.6**	**77.3%**

Table 5.6: Reduction of carbon dioxide emissions by CCS technologies in the 60% RES scenario

Already in the 60% RES scenario for Spain´s power sector, the carbon dioxide emissions would decrease drastically compared to the linear baseline scenario without CCS. In the linear baseline scenario without CCS the power sectors CO_2 emissions from coal- and gas-fired power stations would reach around 145.7 Mt by 2050. Compared to the power sector´s CO_2 emissions of the subsector “Public Electricity and Heat Production” (64.3 Mt in the year 1990) the emissions would more than double until 2050 (+127%). By applying CCS technologies for all gas- and coal-fired power stations with a capture efficiency of 90%, the emissions could be reduced to 14.6 Mt. This equals a reduction of ca. 77% compared to 1990 levels.

[120] IEA – International Energy Agency (2009c, p. 124)

However, considering the objective of the European Union in reducing GHG emissions (-50% by 2050 compared to 1990 on a global level), this translates in an almost complete decarbonization (-95%) of the power sector. In this case the maximum carbon dioxide emissions of Spain´s power sector would be limited to 3.2 Mt – a value which is almost 5 times lower than the calculated CO_2 emissions in the 60% RES scenario. As it is the case for Portugal's power sector analysis, assumptions considered in the analysis lead to high uncertainties in the results. It is expected that carbon dioxide emissions of Spain´s power sector can be reduced by 95% by 2050 out of the following reasons:

- Spain´s national energy strategy aims to cover 40% of the electricity produced in 2020 by RES.[121] As in 2007 the share of RES on electricity generation was ca. 20%, it is expected that in case that growth rates for RES stay on the same level as now, the contribution of RES on total electricity generation will be >60% by 2050.
- The author expects that the increase in electricity consumption/generation will slow down and not follow the linear baseline scenario assumed before. Policy trend shows in this direction and is confirmed by Spain´s "National Renewable Energy Action Plan 2011-2020", which estimates the increase in final electricity demand over preceding years in 2020 with 2.95% while in 2005 the increase compared to the previous year was still 4.58%.[122] This results in less electricity generated also by gas- and coal-fired power plants compared to the linear baseline scenario which assumes 750 TWh of electricity consumption and generation by 2050.
- Carbon dioxide emissions of Spain´s power sector show significant annual variations due to the high share of hydroelectric power plants. Electricity generation out of hydropower depends on fluctuations in annual precipitation. It is questionable if the baseline year 1990 is representative for averaged hydropower production.
- Currently the considered values for specific carbon dioxide emissions for coal-fired power plants are above the European average of 0.881 kg CO_2/kWh.[123] It is expected that specific CO_2 emissions will probably decrease in the future due to efficiency improvements, helping to increase the reduction of CO_2 emissions per unit of electricity generated (kg CO_2/kWh) and therefore increasing the emission reduction.

In the 80% RES scenario, in which only 10% of national electricity generation has to be covered by gas- and coal-fired power plants using CO_2 capture technologies, it is possible to reduce the carbon

[121] Gobierno de España (2010, p. 45)

[122] Gobierno de España (2010, p. 39)

[123] Dubios (2008, p. 8)

dioxide emissions by 92.7% (EU-average of 0.881 kg CO_2/kWh for coal-fired power plants is considered). Limiting in addition the average annual increase in electricity generation to 0.8%, the country´s total electricity generation will reach ca. 419 TWh in 2050, resulting in a carbon dioxide emission reduction of 95.9%. Even though this represents a rough estimation, the increase in electricity generation (419 TWh by 2050) follows the results of the study "Roadmap 2050". In this study the increase in power consumption for Europe was estimated with +42.03% (from 3450 TWh in 2005 to 4900 TWh in 2050). Assuming the same increase within the same period for Spain´s power sector this results in a power consumption of 415.71 TWh in 2050. However, absolute necessities to reach a 95% reduction of CO_2 emissions in Spain´s power sector (in which national consumption equals national generation) are:

- Having a share of 80% of RES in national electricity generation.
- Political decision for electricity generation by nuclear power plants (ca. 42 TWh) also by 2050 or to increase the share of RES to 90%.
- To limit average increase in electricity consumption to 0.8% per year (419 TWh by 2050), which requires strict measurements in energy efficiency improvements over the whole value chain.
- Improving the efficiency of coal- and gas-fired power plants to decrease the specific carbon dioxide emissions (kg CO_2/kWh).
- To apply CCS technologies in all existing conventional, fossil fuel fired power plants. Not capturing CO_2 from gas-fired power plants would limit the reduction to 85%.

A CO_2 reduction target close to 95% by 2050 compared to 1990 levels for Spain´s and Portugal's power sector is technical feasible when considering the economic potential of RES in these countries. For reaching this ambitious goal by 2050 an absolute necessity is to apply aggressive energy efficiency measures to limit electricity consumption to the mentioned values, to increase the share of RES on total electricity generation to 80% (60% RES will not lead to a reduction of 95%) and to apply carbon capture technologies for all remaining gas- and coal-fired power plants in the generation portfolio. In the following table the measurements taken and the resulting reduction in CO_2 emissions for Portugal's and Spain´s power sector in the different scenarios are summarized.

Country	Electricity consumption/ generation by 2050	Share of RES [%]	Share of Coal- and Gas-fired PP´s [%]	Specific CO_2 emissions [kg/kWh] (Coal/Gas)	Capture Efficiency	Reduction of CO_2 with CCS [%]
Portugal	130 TWh	60%	40%	0,930 / 0,365	90%	**76**
		80%	20%	0,930 / 0,365	90%	**88**
	76 TWh	60%	40%	0,881 / 0,365	90%	**86.5**
		80%	20%	0,881 / 0,365	90%	**93.2**
Spain	750 TWh	60%	30%	0,930 / 0,365	90%	**77.3**
		80%	10%	0,930 / 0,365	90%	**92.4**
	419 TWh	60%	30%	0,881 / 0,365	90%	**87.8**
		80%	10%	0,881 / 0,365	90%	**95.9**

Table 5.7: Reduction of carbon dioxide emissions by applying CCS technologies in the different scenarios

6. Economical feasibility of CCS technologies

The following chapter concentrates on the analysis of the economical feasibility of CCS technologies in the Iberian power sector. The deployment of CCS technologies as required in the power sector scenarios for 2050 will strongly depend on the economical competitiveness with alternative/conventional electricity generation technologies. To reduce Portugal’s and Spain´s power sector related CO_2 emissions by 95% by 2050 implies an electricity generation portfolio mainly based on RES, CCS based conventional power plants and nuclear power plants. Political will against CCS based power plants and/or nuclear power plants will increase drastically the required share of RES on total electricity generation in order to fulfill the ambitious target of reducing the carbon dioxide emissions by 95%. A power sector based on almost 100% electricity generation out of RES relies on extended infrastructure for the power grid, the necessity for imports from North Africa and probably also higher backup capacities. The study “Roadmap 2050” analyzed a 100% RES scenario for Europe´s power sector by 2050, concluding that power grid infrastructure requires undersea HVDC cables to import electricity from North Africa and therefore a reinforced transmission grid within Europe. All the necessary power grid investments together result in additional capital requirements of € 225 billion, roughly doubling the capital requirements for the 80% RES scenario pathway.[124]

Applying CCS technologies for fossil-fuel based power plants results in additional investment costs and higher variable costs due to the necessity of capturing, transporting and sequestration CO_2. All these costs increase the short-run marginal costs (SRMC), long-run marginal costs (LRMC) of the power plant and therefore the total electricity generation costs (full-costs). The "cost of CCS" can be defined as the additional full cost (including initial investments and operational expenditures) of a power plant using CCS technology compared to the cost of a state-of-the-art non-CCS power plant, with the same net electricity output and using the same fuel. All costs of all the components of the value chain have to be considered, which mainly can be attributed to CO_2 capture at the power plant, its transport to the sink and permanent storage in the sink. In estimating the costs for CCS there is a high degree of uncertainty due to variations between projects´ technical characteristics, its scale and application as well how costs will develop with time (learning rates and scale benefits). Besides that it is also difficult to estimate the input costs such as steel, engineering and fuel.[125] On the other hand under the EU-ETS the created price for CO_2 emission allowances is also increasing the variable- and full costs for fossil-fuel based power stations without CCS. The increase in variable- and full costs due to the CO_2 price depends on the fuel used in the power plant. As the specific carbon dioxide emissions of coal-fired power plants are higher as of gas-fired power plants, the variable costs will increase more for coal-fired power plants (a constant gas-coal price ratio is assumed). Therefore the economical viability of CCS power plants will strongly depend on:

- The price of CO_2 emission allowances
- Development of fuel and other variable costs
- Development of capital expenditures (CAPEX)
- Development of operational expenditures (OPEX)
- The price for capturing, transporting and long-term storage of CO_2

[124] Roadmap 2050 (2010, p. 77)

[125] Campbell / Nauclér / Ruijs (2008, p. 14)

Therefore learning rates and scale benefits for CCS technologies will be crucial for the deployment of this technology. In this chapter the author will analyze the mentioned factors which influence the economical conditions for CCS technologies in the power sector.

6.1 Carbon prices and merit order

As in 2012, after the second carbon trading period, the Kyoto commitments will finish, new climate policy is required to reach the ambitious target of reducing worldwide GHG emissions by 50%. For a Post-Kyoto trading period the European Commission released a package of measures to accomplish the goals laid out by the European Council of Ministers for 2020, with specific legislative proposals to cut GHG emissions in Europe (also known as "202020" proposal). This package includes an independent EU commitment to achieve at least a 20% reduction of greenhouse gases by 2020 compared to 1990 levels and an objective for a 30% reduction by 2020 subject to the conclusion of a comprehensive international climate change agreement. In the package of measures free allocations to the power sector are forbidden from 2013 onwards and free allocations of carbon credits to other industries will gradually decline to zero by 2020.[126] It is expected that the carbon price for emission allowances will therefore increase. Under a functioning market within the EU-ETS, the price for CO_2 emission rights is determined by the marginal cost of CO_2 abatement. An increase in the price for carbon dioxide, will lead to higher SRMC for electricity production out of coal- and gas-fired power stations. The slope of increase is determined by the specific carbon dioxide emissions of the fuel. As coal-fired power stations have higher specific carbon dioxide emissions, they will face a sharper increase in variable costs (SRMC) as gas-fired power stations. As a result there will be a shift in merit order depending on the carbon price and the gas/coal price ratio. As higher the gas price in relation to the coal price, as higher the breakeven price of carbon for a change in merit order. The following graph illustrates the shift of merit order in dependency of the gas/ coal price ratio and the resulting CO_2 break even point in US$/ton.

[126] Van der Laan (2009, p. 28)

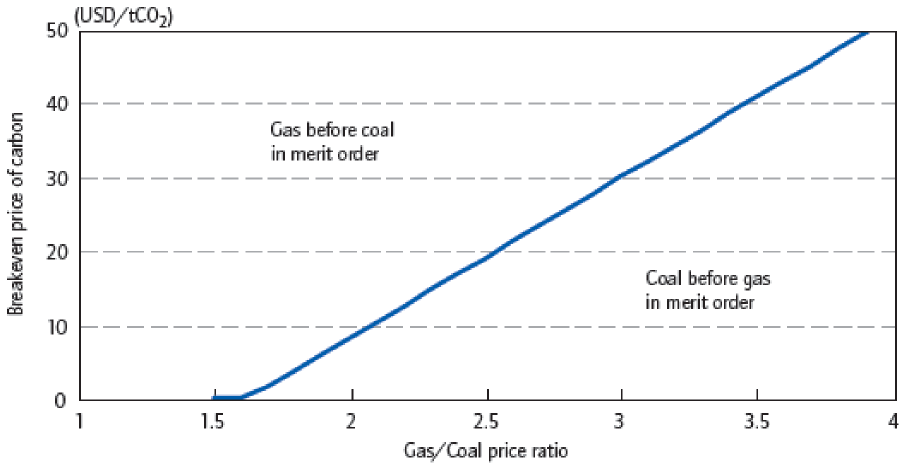

Figure 6.1: Break-even price of carbon at which coal and gas would change places in the merit order. (Source: International Energy Agency (2007b), Climate Policy Uncertainty and Investment Risk)

As higher the coal price, respectively as lower the gas price, also as lower the gas/coal price ratio will be. This results in a lower break-even price for carbon and therefore the gas-fired plant is dispatched instead of the coal-fired plant. The price gap between the SRMC of the two different technologies mentioned has to be covered by a sufficient high CO_2 price. As soon the threshold price of CO_2 is reached there will be a shift in the merit order. In the calculations made to obtain the graph above, the gas-fired power plant efficiency is taken into account with a factor of 1.5 times greater than the coal-fired power plant efficiency. The variable operation and maintenance costs were assumed with 3.33 US$/MWh and 1.5 US$/MWh for gas- and coal-fired power plants respectively. Other assumptions would lead to a change in the position and angle of the break-even line.[127] As electricity price depends on the SRMC of the power plant on the margin, also the carbon dioxide price will have influence on the electricity price. The next graph shows the dependency of the electricity price on the SRMC of the power plant which is on the margin of the merit order and therefore on the carbon price.

[127] International Energy Agency (2007b, p. 50)

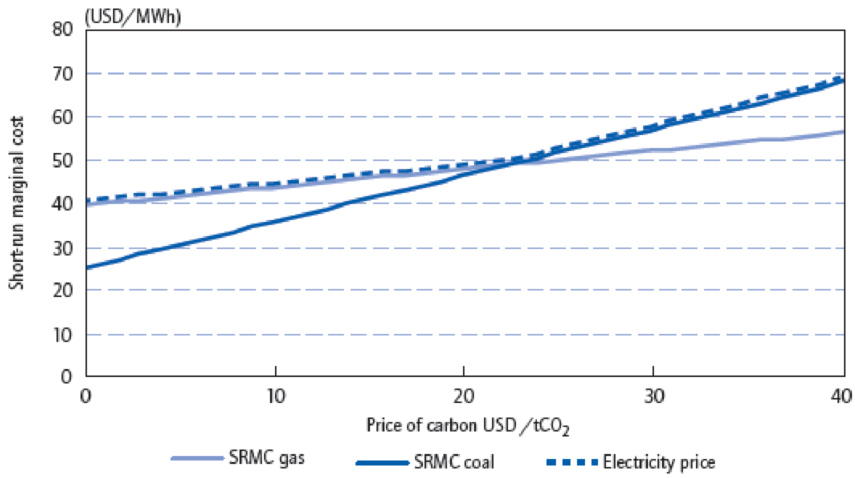

Figure 6.2: Effects of carbon price on the merit order (Source: International Energy Agency (2007b), Climate Policy Uncertainty and Investment Risk)

The graph illustrated above is based on a gas/coal price ratio of 2.7. This means that the gas price is 2.7 times higher as the coal price.[128] At lower carbon prices the SRMC of the coal-fired power plant are lower as the ones of the gas-fired power station. The market price setter will be the gas-fired power station in order to fulfill the electricity demand. At a carbon price above ca. 23 US$/ton CO_2 the short-run marginal costs of the gas-fired power plant will be lower as the ones of a coal-fired power plant and therefore the merit order will change. Electricity price setter will be the coal-fired power station at the margin.

Carbon dioxide prices are expected to rise in the post-Kyoto period and therefore variable costs for power generation out of coal- and gas-fired power stations in Portugal and Spain will also increase. Depending on the development of the gas/coal price ratio, there will be a shift in merit order or not. As the full costs of a power plant have to be earned over time by the contribution margin, the variable costs play a major factor in the profitability of a power plant. Under given circumstances coal-fired power stations have usually lower variable costs than gas-fired power stations but the total investment costs are much higher. The higher contribution margin at a certain time due to the lower variable costs of a coal-fired power station allows the coal-fired power station to operate more hours in a year under a certain price duration curve (base load power plant) and decrease therefore electricity generation costs. As already mentioned before, a change in the variable costs due to higher carbon prices will affect the profitability of a certain power plant and can make gas fired power stations more profitable than coal-fired ones. The following graph illustrates the contribution margin of a gas- and coal-fired power station for a representative price duration curve, as described above.

[128] International Energy Agency (2007b, p. 52)

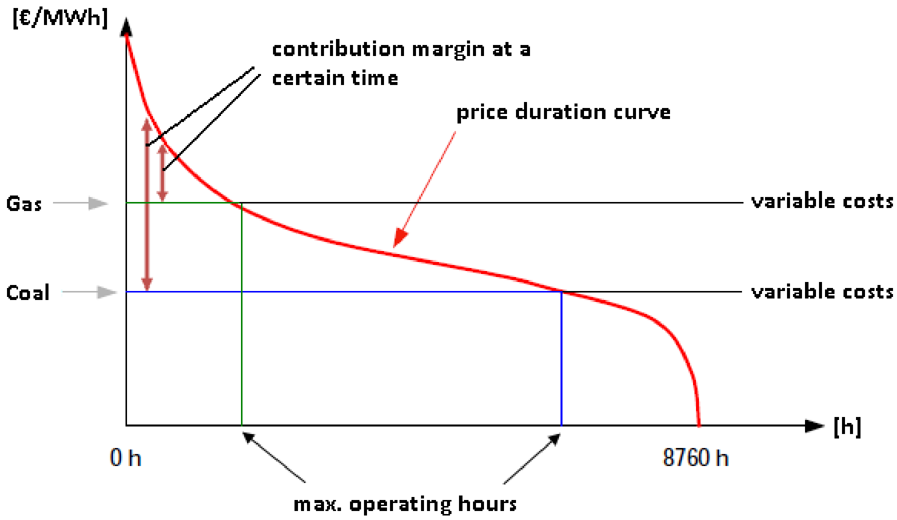

Figure 6.3: Price duration curve and contribution margin of gas- and coal-fired power stations (Source: Zimmermann, Stephan (2010), E.ON Kraftwerke, Energie 2030 und Energiemix, 6. Kraftwerksforum, Stade (*E.ON power plants, Energy 2030 and Energymix, 6. Power plant symposium, Stade*))

Higher investment costs for CCS based power plants might make, depending on the carbon prices and therefore the variable costs, electricity generation out of RES more competitive with the conventional CCS based power stations. The following formula exemplifies the electricity generation costs for a power plant:

$$LCOE = \frac{\sum_{t=0}^{T} \frac{ICo + OPEXt + FCt}{(1+i)^t}}{\sum_{t=0}^{T} \frac{NetEG}{(1+i)^t}} \qquad (1)$$

LCOE	Levelized Cost of Electricity Generation
IC	Investment Costs
OPEX	Operational Expenditures
FC	Fuel Costs
NetEG	Net-Electricity Generation
a	Annuity Factor
i	Interest Rate (representing the WACC)
t	Depreciation time

The annuity factor is determined by the weighted average cost of capital (WACC), representing the interest rate of the investment, and the depreciation time of the power plant.

$$a = \frac{i \times (1+i)^t}{(1+i)^t - 1} \qquad (2)$$

An increase in investment costs for fossil fuel based power plants due to additional investment for CCS technologies or higher variable costs for conventional power plants without CCS technology will increase the electricity generation costs for fossil fuel based power plants. In addition it is expected that learning curves can be applied for all power plants using RES, helping to decrease their high specific investment costs. As main electricity generation technologies based on RES are usually characterized by lower full-load hours (e.g. wind) due to fluctuations in the primary energy source, the power station will produce less electricity in the same period of time as a conventional power plant with the same nominal power (Pn). Therefore the low variable costs of RES and an approximation of investment costs due to learning rates to conventional power generation technologies are crucial in order to reach economical competitiveness with coal- and gas-fired power stations. Independent from the price duration curve and therefore variable costs, feed-in tariffs in Portugal and Spain guarantee a certain price for renewable energy based electricity generation, aiming to decrease their electricity generation costs by scale effects.

In the following the author will make the attempt to estimate the electricity generation costs for different power generation technologies in Portugal's and Spain's power sector by 2050, with the objective to research the competitiveness of renewable energy based electricity generation technologies with CCS-based gas-fired and coal-fired power stations. Furthermore it serves to estimate, if CCS-based power plants will by 2050 be competitive with conventional, fossil-fuel based power plants without CCS. The induction of CCS technologies in the power sectors of Spain and Portugal by 2050 will strongly depend on the development of cost structure (CO_2 price, fuel costs and learning rates for CCS technologies).

6.2 Development of electricity generation costs

The development of the portfolio of a electricity utility company is based on long-term decisions due to the long technical useful life of power generation technologies and technical, economical and ecological requirements have to be considered in the decision making process. The important technical-economical parameters which have to be considered are the specific investment costs, fix and variable costs and as well full load hours (capacity utilization), nominal power and efficiency of the power plant.

The specific investment costs of a power plant are the capital costs in relation to the installed electrical power in €/kW. They include costs which can be attributed directly and indirectly to the construction and commissioning of the power plant. The interest paid are not included in the specific investment costs but are considered by the capital value at the time of power plant commissioning. The costs of plant operation (OPEX) include all costs which can are related to maintenance of the power plant, costs for personnel, administration or insurance and operating- and auxiliary material of electricity production. Fuel costs, costs for CO_2 certificates or transportation- and storage costs for carbon dioxide in case of CCS power plants are not included in the position of the operational expenditures (OPEX). The operational expenditures can be classified in fix and variable OPEX (€/kW respectively €/kWh). The mentioned costs for fuel and carbon certificates are considered separately and in case of CCS technologies also the capture efficiency has to be considered.

The power plant technologies considered in the calculations are conventional coal- and gas-fired power stations, nuclear power plants, CCS based power stations and the RES with the highest economic potential, namely hydro power, wind power (onshore and offshore), solar power (CSP) and biomass. Technical and economical data for the following calculation of specific electricity generation costs respectively LCOE (Levelized Cost of Electricity Generation) are illustrated in the following tables. In a first attempt the LCOE were calculated for power plants commissioned by 2015, respectively 2025 for CCS based power plants. The technical and economical data are considered to be representative for the year 2015. In a second attempt learning rates for the different electricity generation technologies are applied, in order to estimate the specific investment costs in the year 2050.

The decision for a certain type of conventional power plant in the generation portfolio is related to fuel demand, which depends on the efficiency of the plant. Therefore it is important to estimate the development of fuel prices (primary energy) over the life time of the power plant (from commission until decommission). Resulting uncertainties in the fuel price development lead to investment risks in a certain extent, as there is no secure method to forecast prices which are determined by offer and demand on the market.

[€$_{2007}$/MWh]	Price path	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Hard coal	Basis	7,67	8,82	9,43	10,04	10,66	10,91	11,02	11,09	11,20	11,30
	Alternative	7,67	8,21	8,82	9,43	9,58	9,68	9,76	9,83	9,86	9,94
Natural gas	Basis	25,85	29,99	33,37	35,86	37,66	38,84	39,56	40,32	40,68	41,03
	Alternative	25,85	28,87	30,71	31,97	32,83	33,30	33,59	33,84	33,98	34,09
Nuclear energy	Basis	2,92	2,95	2,95	2,74	2,74	2,56	2,56	2,56	2,56	2,56
	Alternative	3,78	3,78	3,78	3,56	3,56	3,38	3,38	3,38	3,38	3,38
Biomass	Basis	21,60	21,60	21,60	21,60	21,60	21,60	21,60	21,60	21,60	21,60

Table 6.1: Development of primary energy prices between 2005 and 2050 in “Basis” and “Alternative” scenario (Source: University of Stuttgart (2008b, p. 14))

The uncertainties about the development of primary energy prices in the future and prices for CO_2 certificates are considered in the calculation of the LCOE – A sensitivity analysis for the LCOE is carried out in dependency of the fuel prices. In this sensitivity analysis the range of fuel prices is determined by the “Basis” price path as highest level and the “Alternative” price path as lowest considered price. For the calculation of the LCOE the average value of the fuel price during the technical useful life of the power plant is considered. Furthermore the sensitivity of LCOE on changes in the price for CO_2 certificates is analyzed. The range is limited to max. 50 €/t CO_2.

In the case of CCS-based power plants carbon dioxide in large amounts has to be transported and stored in proper geological formations as described in the previous chapter. Taking into account the reference coal-fired power station with 740 MW of nominal power, 7450 full-load hours and a capture efficiency of 90% (as assumed in previous calculations), around 5 Mt of CO_2 per year have to be transported and sequestrated. For such large quantities transportation via pipelines is the economical and technical most viable possibility, as already explained in chapter 2.3. In comparison to the transportation costs for CO_2, which are mainly depending on the source-sink distance, the costs for carbon dioxide storage are related to much higher uncertainties, as they depend on storage depth, amount of CO_2 and development costs.[129] The costs for transport and storage of the captured CO_2 considered in the following calculations are based on the estimations by the IPCC, in which the costs

[129] University of Stuttgart (2008b, p. 12)

for transport of carbon dioxide via onshore pipelines have a linear dependency on source-sink distance, as illustrated in the following graph.

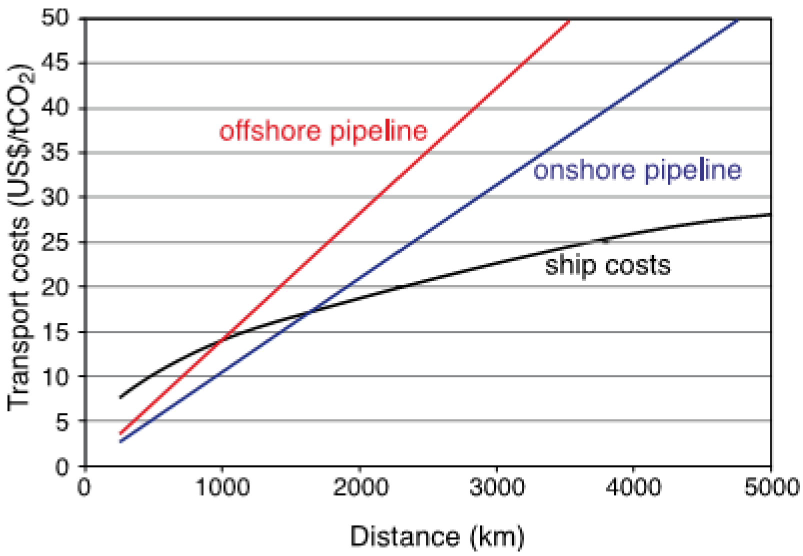

Figure 6.4: Costs for CO_2 transport (pipeline and ship) in dependence on source-sink distance (Source: IPCC (2005, p. 192).

The costs for CO_2 transported illustrated above include intermediate storage facilities, harbour fees, fuel cost and loading/unloading activities. Furthermore also additional costs for liquefaction compared to compression are included.[130] As Portugal's and Spain's power sector show a relatively good relation between carbon dioxide large-point sources and potential sinks on mainland (source-sink matching), as analyzed in chapter 3.2, the transportation costs will in theory be quite low. In the source-sink analysis, the largest distance between CO_2 source and possible sink was found in Spain in the region of Carboneras (Almeria), where the distance to the next sink is about 300km. In some regions there are more than one carbon dioxide LPS situated within the area of potential CO_2 storage sides (e.g. region of Andorra, Gijón, Algeciras, Huelva, Sines and the Setúbal Peninsula). Considering the 300km as reference for estimating the price of CO_2 transport on the Iberian Peninsula, the costs will be around 2.5 US$/t CO_2. Furthermore the costs for CO_2 transport depend on the amount of carbon dioxide transported. Considering a transportation distance of 230 km and a mass flow rate of ca. 6 Mt CO_2/year, the transportation costs would be around 2 USS/t CO_2. As the highest carbon dioxide emissions on the Iberian Peninsula are related to the coal-fired power station "Central Termoeléctrica de Sines" with emissions of ca. 5.8 Mt of CO_2 per year and the largest distance between source and sink is considered to be 300 km, the estimation of 2.5 US$ per ton of CO_2 is reasonable.

[130] IPCC (2005, p. 192)

As the predominant type of possible carbon dioxide storage opportunity on the Iberian Peninsula are saline aquifers, the cost considered for CO2 storage in the following LCOE calculation are based on this type of storage. Furthermore saline aquifers represent by far highest storage capacities in Portugal and Spain with a total, potential storage capacity of ca. 325 Mt for Portugal and ca. 23.4 Gt for Spain. According to the IPCC report, onshore storage cost for saline formations in Europe for depth of 1000-3000m are 1.9 – 6.2 US$/t CO_2, with a most likely value of ca. 2.8 US$/ t CO_2.[131] Assuming transport costs of 2.5 US$/t CO_2 and storage costs of 2.8 US$/t CO_2 for saline aquifers on the Iberian Peninsula, the total cost of transport and storage of carbon dioxide will be around 5.3 US$/t CO_2. Considering the current exchange rate of 1.3795[132], this equals onshore pipeline transport costs of ca. 1.8 €/t CO_2 and saline aquifer based storage costs of ca. 2.0 €/t CO_2. In total this results in transport and storage costs for the Iberian Peninsula of around 4 €/t CO_2.

All the data used for LCOE calculations for the different electricity generation technologies considered is based on scientific literature and papers and in each case listed below the calculation tables. Data, which is not documented explicitly by a reference, is always based on the study "Roadmap 2050 – A practical guide to a prosperous, low-carbon Europe" as listed in the bibliography of the thesis. The interest rate assumed for all power generation technologies is assumed to be 7.5%. Variations in the interest rate would significantly change the LCOE, that's why the interest rate is the same for all technologies.

6.2.1 LCOE in comparison for commissioning by 2015

In the following, the LCOE of the different power generation technologies considered for a commissioning by 2015 are calculated and analyzed. Furthermore the sensitivity of the LCOE on changes in fuel prices and CO_2-certificate prices is researched. The table shown on the following page illustrates the technical and economical parameters for reference power plants in the year 2015 (2025 for CCS based power plants respectively).

[131] IPCC (2005, p. 261)

[132] X-Rates (2011)

Energy carrier	Hard coal	Natural gas	Hard coal	Natural gas	Nuclear power	Hydro	Wind	Wind	Solar	Biomass
Type of power plant	Steam power plant	GTCC	CCS - 2025	CCS - 2025	Pressure water reactor	Run-off river power plant	Onshore	Offshore	CSP	Dedicated
Electrical net-efficiency[4] [%]	46	60	37,5	50	36					30
Technical useful life[4] [a]	40	30	40	30	60	60	20	20	25-30[1]	20
Capacity utilization[8] [%]	85	85	85	85	85	57	15-25	25-40	20-90[2]	85
Specific CO_2 emissions [t/MWh]	0,930	0,365	0,093	0,0365	-	-	-	-	-	-
CAPEX 2015[4] [€/kWel]	1300	700	2200	1400	2800	4982[8]	1050[8]	1950[8]	5000[3]	2350
Learning rate [%]			12	12	3		5	5	HC[3]	
Yearly reduction [%]	0,5	0,5				0,5				1
OPEX [4] [€/MWh]	4	2	5	3,4	0,5	20[6]	-	-	9,32[7]	
OPEX [4] [€/kW]	35	19	65	55	55	-	50	120	-	100[9]
Fuel costs[4] [€/MWh]	10,71	38,42	11,03	39,68	2,65	0	0	0	0	21,60
CO_2 price for EUA [€/t] [5]	12,27	12,27	12,27	12,27	-	-	-	-	-	-
Transport& Storage [€/t]			4	4						
Pn [4] [MW]	800	800	740	800	1600	3,1[8]	3	5	50[2]	20

(1) Data source: Federal Ministry of the Environment (2010, p. 4)
(2) Data source: MED-CSP (2005, p. 10)
(3) Hardcoded input based on workshop
(4) Data source: University of Stuttgart (2008b, p. 7, 11, 14)
(5) Data source: European Energy Exchange (2011)
(6) Data source: IEA (2010c, p. 3)
(7) Data source: Kaplan (2008, p. 39)
(8) Data source: University of Stuttgart (2008a, p. 3)
(9) Data source: IEA ETSAP (2010, p. 1)

Table 6.2: Technical and economical parameters for reference power plants (Commissioning by 2015)

The graph and table shown below illustrate the LCOE and their composition of the different electricity generation technologies considered for a commissioning by 2015 (2025 for CCS based power plants respectively). All data necessary for the LCOE-calculations can be consulted in the table before or in the text in the previous pages.

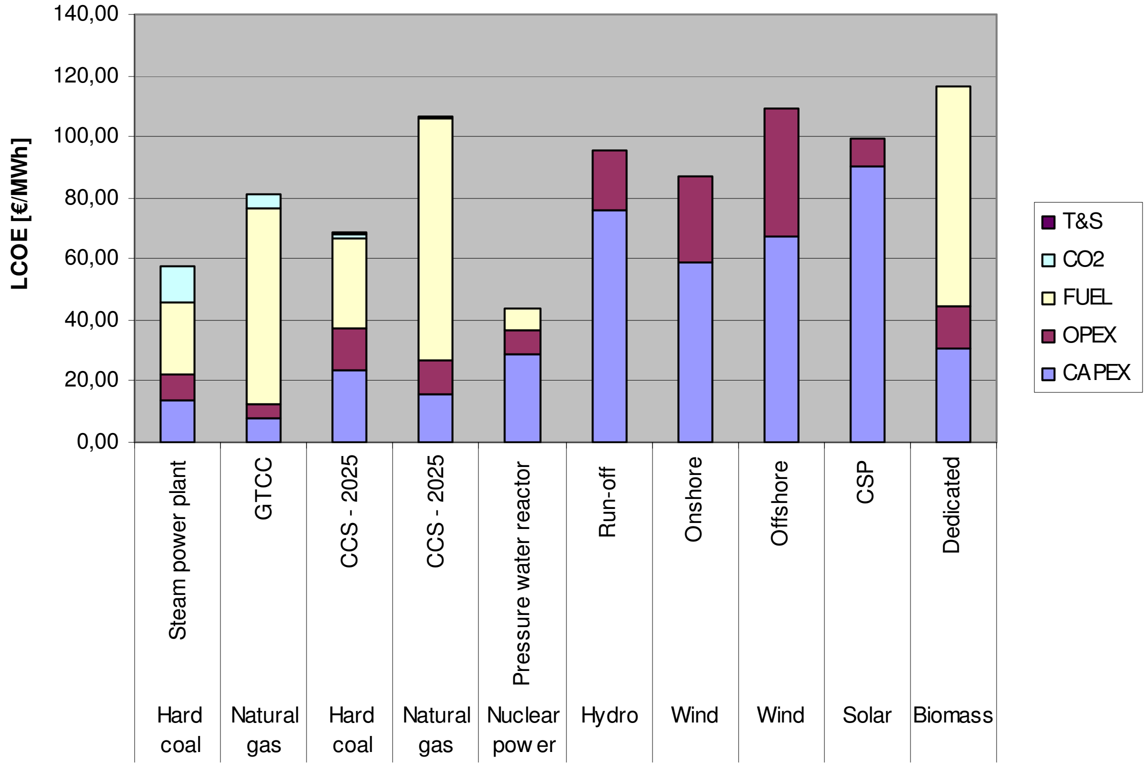

Figure 6.4: LCOE of different electricity generation technologies by 2015

Energy carrier	Type of power plant	CAPEX	OPEX	FUEL	CO_2	T&S	Total
		[$€_{2007}$/MWh]					
Hard coal	Steam power plant	13,86	8,70	23,28	11,41		**57,26**
Natural gas	GTCC	7,96	4,55	64,03	4,48		**81,02**
Hard coal	CCS - 2025	23,46	13,73	29,41	1,14	0,99	**68,74**
Natural gas	CCS - 2025	15,92	10,79	79,36	0,45	0,29	**106,81**
Nuclear power	Pressure water reactor	28,58	7,89	7,36			**43,82**
Hydro	Run-off	75,82	20,00	0,00			**95,82**
Wind	Onshore	58,79	28,54	0,00			**87,33**
Wind	Offshore	67,19	42,15	0,00			**109,34**
Solar	CSP	90,17	9,32	0,00			**99,49**
Biomass	Dedicated	30,96	13,43	72,00			**116,39**

Table 6.3: Elements of LCOE for different electricity generation technologies by 2015

As shown in the table and graph above, the current price for CO_2 certificates compared with the higher specific CAPEX, OPEX and fuel prices for CCS based coal-fired power plants results in LCOE of

68.73 €/MWh of electricity generated. Compared to conventional coal-fired power stations (57.26 €/MWh) the LCOE are around 20% higher. For gas-fired power stations the difference is due to the relatively low CO_2 emissions of conventional gas-fired power stations even more significant (ca. + 32% in LCOE).

When analyzing the LCOE of RES, it can be concluded that the current high specific investment costs (€/kW) and low full-load hours compared to conventional power generation technologies are the main reason for the high LCOE. Support mechanisms such as feed-in tariffs for RES based electricity generation aim to reduce the currently high specific investment costs and to benefit for scale-effects. Therefore it is expected the RES will be in the future competitive with conventional power generation technologies, also because of higher fuel costs for coal- and gas-fired power stations.

6.2.2 LCOE in comparison for commissioning by 2050

In the following, the LCOE of the different power generation technologies considered for a commissioning by 2050 are calculated and analyzed. The table shown on the following page illustrates the technical and economical parameters for reference power plants in the year 2050. The main change can be found in the specific investment costs (learning rates are applied) and in the price for CO_2-certificates. Furthermore it is expected that fuel prices for hard coal and natural gas will increase. The fuel prices for a commissioning by 2050 can be consulted in table 6.1 ("Development of primary energy prices between 2005 and 2050 in "Basis" and "Alternative" scenario"). For simplification and due to a lack of data beyond 2050 prices for natural gas are expected to be 41.03 €/MWh and 11.03 €/MWh for hard coal. Besides that CO_2-price is expected to be at least 20 €/t.

Energy carrier	Hard coal	Natural gas	Hard coal	Natural gas	Nuclear power	Hydro	Wind	Wind	Solar	Biomass
Type of power plant	Steam power plant	GTCC	CCS – 2025	CCS - 2025	Pressure water reactor	Run-off river power plant	Onshore	Offshore	CSP	Dedicated
Electrical net-efficiency[(4)] [%]	46	60	37,5	50	36					30
Technical useful life[(4)] [a]	40	30	40	30	60	60	20	20	25-30[(1)]	20
Capacity utilization[(8)] [%]	85	85	85	85	85	57	15-25	25-40	20-90[(2)]	85
Specific CO_2 emissions [t/MWh]	0,930	0,365	0,093	0,0365	-	-	-	-	-	-
CAPEX 2050 [€/kWel]	1075	580	1940	1230	2720	4110	1000	1850	2400	1530
OPEX [(4)] [€/MWh]	4	2	5	3,4	0,5	20[(6)]	-	-	9,32[(7)]	
OPEX [(4)] [€/kW]	35	19	65	55	55	-	50	120	-	100[(9)]
Fuel costs[(4)] [€/MWh]	11,3	41,03	11,3	41,03	2,56	0	0	0	0	21,6
$C0_2$ price for EUA [€/t] [(5)]	20	20	20	20	-	-	-	-	-	-
Transport& Storage [€/t]			4	4						
Pn [(4)] [MW]	800	800	740	800	1600	3,1[(8)]	3	5	50[(2)]	20

[(1)] Data source: Federal Ministry of the Environment (2010, p. 4)
[(2)] Data source: MED-CSP (2005, p. 10)
[(3)] Hardcoded input based on workshop
[(4)] Data source: University of Stuttgart (2008b, p. 7, 11, 14)
[(5)] Data source: European Energy Exchange (2011)
[(6)] Data source: IEA (2010c, p. 3)
[(7)] Data source: Kaplan (2008, p. 39)
[(8)] Data source: University of Stuttgart (2008a, p. 3)
[(9)] Data source: IEA ETSAP (2010, p. 1)

Table 6.4: Technical and economical parameters for reference power plants (Commissioning by 2050)

The graph and table shown below illustrate the calculated LCOE and their composition of the different electricity generation technologies considered for a commissioning by 2050. All data necessary for the LCOE-calculations can be consulted in the table before or in the text in the previous pages.

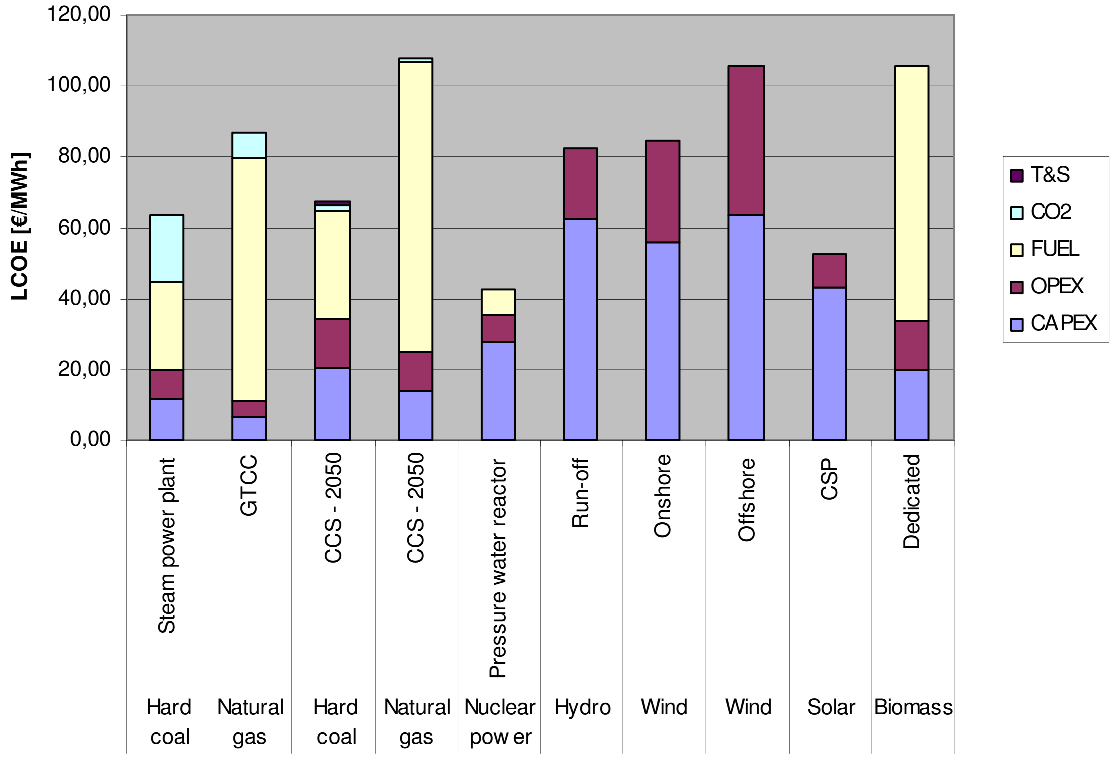

Figure 6.5: LCOE of different electricity generation technologies by 2050

Energy carrier	Type of power plant	CAPEX	OPEX	FUEL	CO_2	T&S	Total
				[$€_{2007}$/MWh]			
Hard coal	Steam power plant	11,46	8,70	24,57	18,60		**63,33**
Natural gas	GTCC	6,60	4,55	68,38	7,30		**86,83**
Hard coal	CCS – 2050	20,69	13,73	30,13	1,86	0,99	**67,40**
Natural gas	CCS – 2050	13,99	10,79	82,06	0,73	0,29	**107,86**
Nuclear power	Pressure water reactor	27,76	7,89	7,11			**42,76**
Hydro	Run-off	62,55	20,00	0,00			**82,55**
Wind	Onshore	55,99	28,54	0,00			**84,53**
Wind	Offshore	63,74	42,15	0,00			**105,89**
Solar	CSP	43,28	9,32	0,00			**52,60**
Biomass	Dedicated	20,16	13,43	72,00			**105,59**

Table 6.5: Elements of LCOE for different electricity generation technologies by 2050

The graph and table above exemplify that learning rates applied to all power plants and a higher price for CO_2 certificates make CCS-based coal fired power stations more competitive with conventional hard coal-fired power plants. Due to the lower efficiency of the CCS power plant (37.5%) compared to the conventional power plant (46%) the €/MWh spend on fuel is significantly higher for the CCS power plant. Due to a carbon price of 20 €/t of CO_2 the total LCOE for the conventional power plant are sharply increasing from 44.73 €/MWh to 63.33 €/MWh while the CCS based coal-fired power station has total LCOE of 67.40 €/MWh. When comparing the LCOE of gas-fired power plants with each other it gets clear that a carbon price of 20 €/MWh is much to low for making CCS competitive with the conventional option. This is due to the fact the natural gas has relatively low specific carbon dioxide emissions (0.365 t/MWh on the Iberian Peninsula). Low specific emissions result in less carbon dioxide certificates necessary and therefore the slope of increase in LCOE with an increase in the CO2 price is much lower as for coal-fired power stations.

As soon LCOE for CCS based, coal-fired power stations are competitive with conventional coal-fired power stations and political frameworks are set in a direction of a massive reduction of carbon dioxide emissions for the power sector and gas-fired power stations will be pushed out of the market in a certain extent. However, as oil-fired power stations are considered to be out of the market by 2050 or earlier due to very high fuel costs, gas-fired power stations will play an important and vital role in peak-load power production, when spot-market prices are very high.

Especially in the power sector of Portugal and Spain a large economic potential in CSP plants is given. It is expected that specific investment costs for this technology will decrease from ca. 5000 €/kW in 2015 to ca. 2500 €/kW by 2050. Besides that the low OPEX of this technology and no fuel costs help to reduce full costs even more. Therefore a massive reduction of LCOE (from 99.49 €/MWh to 52.60 €/MWh) will take place.

6.2.3 Sensitivity analysis of LCOE

To consider the uncertainties in the assumptions for fuel prices and CO_2 certificate prices, the author will carry out a sensitivity analysis of LCOE in order to be able to estimate the break-even point for CCS technologies in the Portuguese and Spanish power sector. In a first attempt the LCOE for coal- and gas-fired power stations are calculated for a carbon dioxide price ranging from 0 to 50 €/t. The fuel price considered in this calculation is assumed to be on 2050 level (41.03 €/MWh for natural gas and 11.30 €/MWh for hard coal). The following graph illustrates the sensitivity of LCOE for conventional coal- and gas-fired power stations and CCS-based power plants.

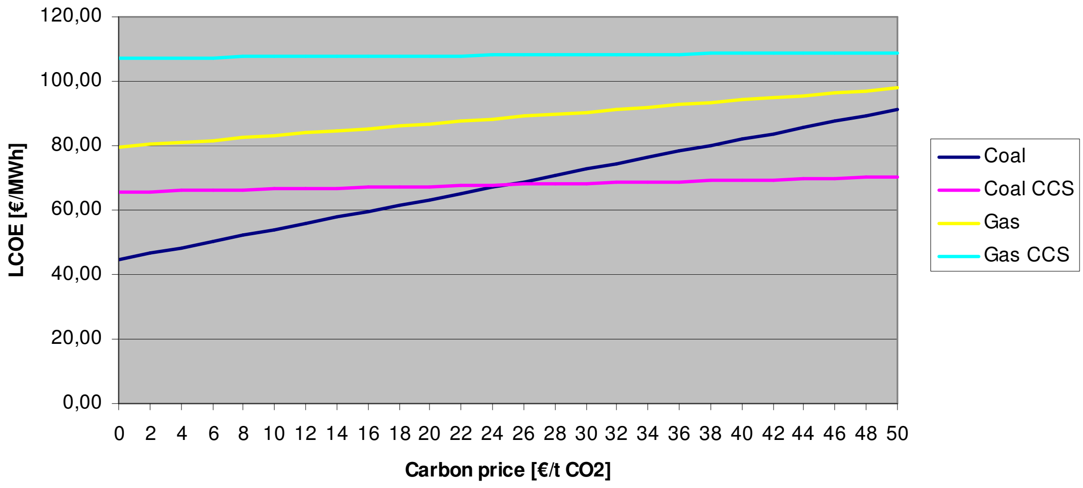

Figure 6.6: Carbon price sensitivity of LCOE of different electricity generation technologies by 2050

The graph above illustrates the sensitivity of LCOE on the carbon price. As coal-fired power stations on the Iberian power sector have significantly higher carbon dioxide emissions than gas-fired power stations also the increase of LCOE with increasing carbon prices is more significant. Due to the capture efficiency applied for CCS power plants of 90%, the slope of the curve is very low. Already at a certificate price for European Emission Allowances of around 25 €/t the power plant technology for hard coal with carbon capture is out of an economical perspective the more viable option. Therefore the break-even price for CCS-based coal-fired power plants by the year 2050 will be around 25 €/t (subject to technical and economical assumptions made). The lower specific carbon dioxide emissions for gas-fired power plants and the resulting small slope will lead to a much higher break-even price. The break even price calculated under the technical and economical assumptions set will be around 83 €/t.

As it is not expected that the carbon price will reach the break-even price of 83 €/t by 2050, conventional GTCC-power plants will be the favored economic option. Out of an ecological perspective (decarbonization of Portugal's and Spain's power sector by 2050), the electricity generation out of GTCC power plants will have to play a minor role in total electricity generation in order to reach the ambitious target of decarbonizing the power sectors. This is expected to happen as CCS-based coal-fired power plants will push GTCC power plants out of the market in a large extent. Gas-fired power plants will mainly be used in peak load power production.

The following graph illustrates the sensitivity of LCOE for conventional coal- and gas-fired power stations and CCS-based power plants on fuel prices. On the horizontal axis the fuel price for hard coal and natural vary from 50% to 150%. The 100% represent 41.03 €/MWh for natural gas and 11.30 €/MWh for hard coal. The carbon price for EUA is considered with a value of 20 €/t.

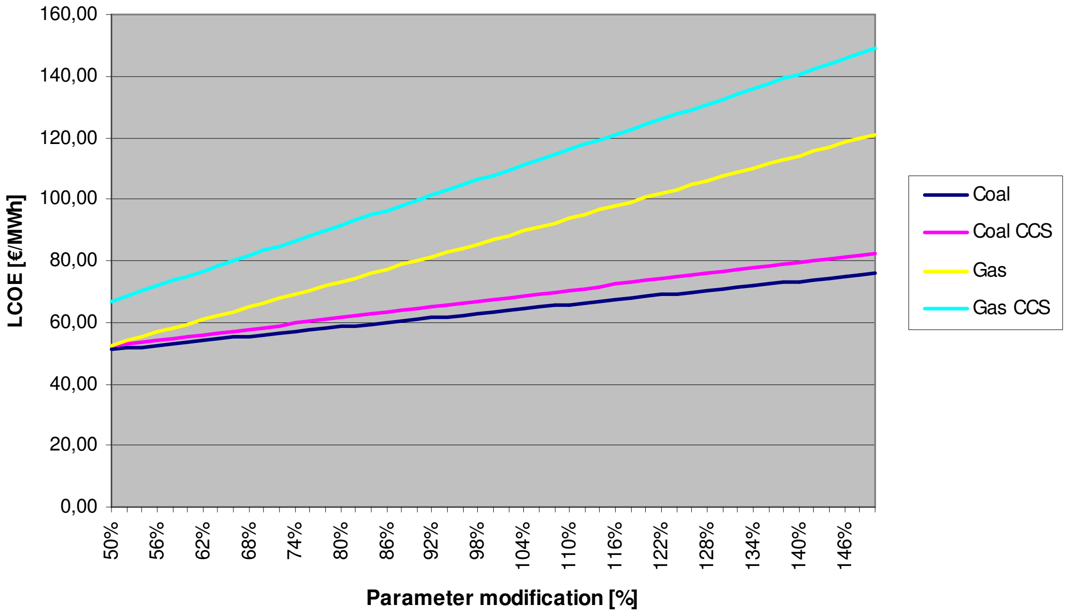

Figure 6.7: Fuel price sensitivity of LCOE of different electricity generation technologies by 2050

As lower fuel costs are getting for natural gas or coal, as less the difference in LCOE between conventional and CCS based power plant. This is related to the lower efficiency of CCS based power plants. As lower the fuel price is getting, as less the fraction of fuel costs on total LCOE, meaning that the lower efficiency of CCS based power plants is compensated. At a hard coal price of ca. < 4.7 €/MWh the CCS based power plant will be the economical more viable option. The sensitivity of LCOE on fuel prices is more significant for gas-fired power plants than for coal-fired power plants, as the fraction of fuel prices on total electricity generation costs is very high. Therefore it can be concluded that CCS based power plants benefit from decreasing fuel prices in a certain extent. However, it is not expected that fuel prices will decrease 50% under the expected values taken into consideration in previous calculations by 2050.

7. Conclusions

The objective of the thesis was to analyze the necessity and technical and economical viability of CCS systems for Portugal's and Spain's power sector, in order to decarbonize the Iberian power sector by 95% by 2050. For that purpose the carbon dioxide LPS (large point sources) of the power sectors and possible storage sides for CO_2 were identified. In the following source-sink matching analysis LPS sources and potential geological sinks were mapped and their proximity analyzed. The source-sink matching analysis for Portugal and Spain has shown that the major part of LPS in the power sector of these countries have a proximity to possible sinks with allow to transport the captured and compressed carbon dioxide under economical viable conditions. Due to a lack of data the cost estimation for CO_2 transport and geological storage on the Iberian Peninsula is very rough and relies on figures taken from literature. Further studies are needed to evaluate the transport and storage for CO2 in more detail. The research project COMET - Infrastructure for CO_2 Transport and Storage in the West Mediterranean will analyze the technical and economical viability in detail.

Furthermore the power sectors of the countries researched were analyzed and the future economic potential of RES for electricity production identified. Especially CSP (Concentrating Solar Power) will play an important and vital role in future electricity generation due to the high economic potential. As 100% RES for electricity generation by 2050 is considered to lead to very high capital investments, two different scenarios were researched. In the first scenario 60% of electricity generation will be covered by RES and the remaining 40% in even shares by CCS based coal- and gas-fired power plants. The second scenario assumes 80% RES and 20% CCS. For Spain in both scenarios nuclear power generation is considered with a share of 10% the share for RES is the same as in the cased study for Portugal (60% RES in the first scenario and 80% in the second). As the analysis of Portugal's and Spain's power sector has shown, it is expected that the required reduction in carbon dioxide by 95% until 2050 is technical feasible. However, it is necessary that national electricity generation for both countries is based by 80% on RES, that average increase in electricity consumption is limited to 0.8% per year and that the efficiency of coal- and gas-fired power plants is increased to at least European average standard. Furthermore nuclear power will have to continuo to play a role in Spain's national electricity generation in order to reach the required reduction in carbon dioxide emissions by 2050. Political decision against nuclear power would significantly increase the required share of RES or CCS based power plants in electricity generation and therefore investment costs would increase. Besides the mentioned sharp increase in RES electricity generation and strict energy efficiency measures, CCS technologies will have to be applied to the major part of the remaining coal- and gas-fired power plants. Not applying CCS technologies for fossil fuel fired power stations would limit the reduction in CO_2 emissions of the power sector to 80% in the case of Portugal and 85% in the case of Spain.

In the last part of the thesis "Economical feasibility of CCS technologies" the economical parameters for different power generation technologies were analyzed and the Levelized Cost of Electricity Generation (LCOE) by 2015 and 2050 calculated. For the calculation of LCOE by 2050 learning rates were applied with are expected to decrease specific investment costs [€/kW] significantly. Furthermore it is assumed that a functioning market for emission trading will lead to significantly higher prices for carbon dioxide emission certificates (EUA). The consideration of fuel prices (hard coal and natural gas) for the year 2050 is based on literature. However, uncertainties in the development in fuel prices and carbon dioxide emission certificates are considered in the calculation of LCOE. These uncertainties are considered in a sensitivity analysis. The results show that already at a certificate price for European Emission Allowances of around 25 €/t the power plant technology for hard coal with carbon capture is out of an economical perspective the more viable than conventional hard coal fired power plants. Therefore the break-even price for CCS-based coal-fired power plants by the year 2050 will be around 25 €/t (subject to technical and economical assumptions made). The lower specific carbon dioxide emissions for gas-fired power plants will lead to a much higher break-even price. The break even price calculated under the technical and economical assumptions set will be around 83 €/t.

Due to uncertainties in political decisions and technical developments it is not clear yet if CCS technologies will be competitive with conventional fossil fuel based power plants. Despite of this uncertainties, it can be concluded that political frameworks set in favor for CCS technologies would help to fulfill the ambitious target of reducing the CO_2 emissions of Portugal's and Spain's power sector by 95%. As additional benefit lower capital requirements for the power sector can be mentioned. A power sector based on almost 100% electricity generation out of RES relies on extended infrastructure for the power grid, the necessity for imports from North Africa and probably also higher backup capacities. The study "Roadmap 2050" analyzed a 100% RES scenario for Europe´s power sector by 2050, concluding that power grid infrastructure requires undersea HVDC cables to import electricity from North Africa and therefore a reinforced transmission grid within Europe. All the necessary power grid investments together result in additional capital requirements of € 225 billion, roughly doubling the capital requirements for the 80% RES scenario pathway.[133] For a scenario in which Portugal' and Spain's power sector is mainly based on RES and the additional electricity generation covered by CCS power plants the full-load hours of CCS power plants would decrease, as RES usually have priority in the merit order. This would have effects on the economical viability of CCS power plants and might also influence the technical feasibility of CCS systems. Therefore additional research in the area of flexible operating power plants using CCS technologies is needed. Although the thesis is based on assumptions for further developments (political decisions, fuel prices etc.) it aims to provide a first integrated approach for the implementation of CCS technologies in Portugal's and Spain's power sector on a technical and economical scale.

[133] Roadmap 2050 (2010, p. 77)

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Annex I – List of installations included in the National Allocation Plan II and related emission allowances

Número de ordem	TEGEE (PNALE I)	Sector	Subsector	Instalação	Operador	LE (t CO2/ano)
1	077.02	Energia/Centrais Termoeléctricas	Carvão	Central Termoeléctrica do Pego	Tejo Energia, Produção e Distribuição de Energia Eléctrica, S. A.,	2 723 011
2	078.01			Central Termoeléctrica de Sines	CPPE — Companhia Portuguesa de Produção de Electricidade	5 833 317
3	057.01		Biomassa	Central Termoeléctrica de Mortágua	O&M Serviços S..A.	1 153
4	058.01		CCGT	Central Termoelétrica do Ribatejo	Companhia Portuguesa de Produção de Electricidade	1 423 103
5	019.01			Central de Ciclo Combinado da Tapada do Outeiro	Turbogás — Produtora Energética, S. A.	1 198 020
6	055.01		Fuel	Central Termoeléctrica do Carregado	Companhia Portuguesa de Produção de Electricidade	377 234
7	059.01			Central Termoeléctrica do Barreiro	Companhia Portuguesa de Produção de Electricidade	138 977
8	054.01			Central Termoeléctrica de Setúbal	Companhia Portuguesa de Produção de Electricidade	1 118 999
9	075.01			Central Térmica do Porto Santo	EEM, S. A.	40 036
10	076.01			Central Térmica da Vitória	EEM, SA	537 383
11	066.01			Central Térmica de Santa Bárbara	Electricidade dos Açores, S. A.	41 638
12	067.01			Central Térmica do Belo Jardim	Electricidade dos Açores, S. A.	153 040
13	068.01			Central Termoeléctrica do Caldeirão	Electricidade dos Açores, S. A.	245 432
14	069.01			Central Termoeléctrica do Pico	Electricidade dos Açores, S. A.	37 773
15	010.01			Central Termoeléctrica do Caniçal	Atlantic Islands Electricity	128 328
16	053.01		Gasóleo	Central Termoeléctrica de Tunes	Companhia Portuguesa de Produção de Electricidade	4 537
17	196.01	Energia/Refinação	Refinação	Refinaria de Sines	Petróleos de Portugal — Petrogal S. A.	2 137 550
18	197.02		Refinação	Refinaria do Porto	Petróleos de Portugal — Petrogal, S. A.	1 098 025
19	004.01	Energia/Cogeração	Agroalimenta	Unicer -Central de Produção combinada de calor e electricidade (Unicer Cervejas S.A -Centro de Produção de Leça do Balio)	UNICER, Energia e Ambiente, S. A	33 560
20	005.01			Unicer -Central de Produção combinada de calor e electricidade (Unicer Cervejas S.A -Centro de Produção de Santarém)	UNICER, Energia e Ambiente, S. A.	10 982
21	012.01			CTE -Central Termoeléctrica do Estuário, L.da,	CTE -Central Termoeléctrica do Estuário, L.da,	22 905
22	009.01			Companhia Térmica Tagol, L.da,	Companhia Térmica Tagol, L.da,	41 603
23	040.01			RAR-Cogeração Unipessoal Lda	RAR-Cogeração Unipessoal Lda	50 577
24	223.01			DAI, Sociedade de Desenvolvimento Agro-Industrial, S. A.,	DAI, Sociedade de Desenvolvimento Agro-Industrial, S. A.	84 008
25	017.01			POWERCER	GALP POWER, SGPS, S. A.	47 192
26	178.01		Agroflorestal	Siaf -Sociedade de Iniciativa e Aproveitamentos Florestais -Energia, S. A. -Mangualde	Siaf — Sociedade de Iniciativa e Aproveitamentos Florestais -Energia, S. A. Mangualde	19 480
27	003.01			Enercaima -Produção de Energia, S. A.	Enercaima -Produção de Energia, S. A.	53 147
28	036.01			Enerbeira -Recursos Energéticos Lda.	Enerbeira — Recursos Energéticos Lda.	41 028
29	016.01			Sonae Indústria — Produção e Comercialização de Derivados de Madeira, S. A. -Oliveira do Hospital (Casca Sociedade de Revestimentos, S.A)	Sonae Indústria — Produção e Comercialização de Derivados de Madeira, S. A.	28 953
30	056.01		Pasta e papel	Central de Cogeração da Soporgen	SOPORGEN — Sociedade Portuguesa de Geração de Electridade e Calor, S. A.	239 306

Número de ordem	TEGEE (PNALE I)	Sector	Subsector	Instalação	Operador	LE (t CO2/ano)
31	025.01			ENERPULP — Cogeração Energética de Pasta, S. A. (Setúbal)	ENERPULP — Cogeração Energética de Pasta, S. A.	65 832
32	022.01			SPCG — Sociedade Portuguesa de Cogeração Eléctrica, S. A.,	SPCG -Sociedade Portuguesa de Cogeração Eléctrica, S. A.	156 099
33	047.02			ENERPULP Lavos	ENERPULP — Cogeração Energética de Pasta, S. A.	85 807
34	144.01			Central de Cogeração de CACIA	ENERPULP — Cogeração Energética de Pasta, S. A.	98 590
35	026.01			Caima Energia: Constância	Caima — Energia, Empresa de Gestão e Exploração de Energia, S. A.	13 476
36	043.02			Portucel Viana Energia	Portucel Viana Energia	206 091
37	060.01		Químico	Central de Cogeração da Energin	ENERGIN -Sociedade de Produção de Electricidade e Calor, S. A.	225 955
38	141.01			Bamiso	BAMISO -Produção e Serviços Energéticos, S. A.	53 613
39	092.01			Selenis Energia, S.A	Selenis Energia, S.A	51 079
40	038.01			Carriço Cogeração	GALP POWER, SGPS, S. A.	161 539
41	176.02			REPSOL — Central Termoeléctrica	Repsol — Produção de Electricidade e Calor, ACE	411 058
42	042.02			ENERLOUSADO — Recursos Energéticos Lda (Continental Malboro)	ENERLOUSADO — Recursos Energéticos Lda	42 469
43	170.01		Têxtil	Saramagos	Saramagos — Soc.Prod.Energia, S. A.	56 675
44	071.01			Lameirinho Recursos Energéticos S. A.	Lameirinho Recursos Energéticos S. A.	38 617
45	01.02			SEVA — Central de produção combinada de calor e electricidade	SEVA — Sociedade Energética de Valdante, S. A.	29 835
46	028.01			SPE-Sociedade de Produção de Electricidade e Calor S. A.	SPE-Sociedade de Produção de Electricidade e Calor S. A.	46 027
47	011.01			Fábrica do Arco — Recursos Energéticos, S. A.,	Fábrica do Arco — Recursos Energéticos, S. A.	26 643
48	006.01			Companhia Térmica do Serrado, ACE	Companhia Térmica do Serrado, ACE	17 712
49	007.01			Companhia Térmica Oliveira Ferreira, ACE	Companhia Térmica Oliveira Ferreira, ACE	11 421
50	008.01			Companhia Térmica Mundo Textil, ACE	Companhia Térmica Mundo Textil, ACE	20 938
51	101.01			MABERA -Acabamentos Têxteis, S. A.	MABERA — Acabamentos Têxteis, S. A.	13 569
52	167.01		Extracção de matéria mineral	Unidade de Cogeração (Adelino Duarte da Mota)	Adelino Duarte da Mota, S.A	48 733
53	027.01		Vários	Central de Cogeração do Parque das Nações	Climaespaço — Soc. Prod.Distrib.Urb. Energia Térmica, S. A.	29 259
54	072.01	Energia/ Inst. de Combustão	Ind. Agroalimentar	Tagol — Companhia de Oleaginosas do Tejo S.A	Tagol — Companhia de Oleaginosas do Tejo S.A	24 328
55	034.01			TATE & LYLE Açúcares de Portugal (ex--Alcântara -Refinarias Açúcares, S. A.)	TATE & LYLE Açúcares de Portugal (ex-Alcântara — Refinarias Açúcares, S. A.)	38 654
56	74.02			Fábrica de Avanca	Nestlé Portugal, S. A.	18 861
57	106.01			Fábrica de Benavente	Indústrias de Alimentação IDAL, L.da,	31 714
58	100.01			Pronicol, Produtos Lácteos, S. A -Instalação Industrial da Quinta de S. Luís, Angra do Heroísmo	Pronicol, Produtos Lácteos, S. A.	24 930
59	211.01			COMPAL — Central Térmica	COMPAL — Companhia Produtora de Conservas Alimentares	13 374
60	085.01			Rogério Leal & Filhos, S. A.,	Rogério Leal & Filhos, S. A.	14 765
61	235.01			Instalação de Combustão (Avilafões)	Avilafões — Aviários de Lafões Lda.	4 195
62	194.01			SUGAL — Alimentos, S. A.,	SUGAL — Alimentos, S. A.	15 678
63	250.01			LACTOGAL — Produtos Alimentares, S. A.	LACTOGAL — Produtos Alimentares, S. A.	11 829
64	254.01			SOPRAGOL — Sociedade de Industrialização de Produtos Agrícolas,S. A.	SOPRAGOL — Sociedade de Industrialização de Produtos Agrícolas,S. A.	8 732
65	256.01			CAMPIL Agro Industrial do Campo do Tejo, L.da,	CAMPIL Agro Industrial do Campo do Tejo, L.da,	5 376
66	248.01			F.I.T. — Fomento da Indústria de Tomate, S. A.,	F.I.T. — Fomento da Indústria de Tomate, S. A.	9 667
67	255.01			Tomsil — Sociedade Industrial de Concentrado de Tomate, S. A.,	Tomsil — Sociedade Industrial de Concentrado de Tomate, S. A.	2 112
68	246.01			ITALAGRO — Indústria de Transformação Alimentar, S. A.,	ITALAGRO — Indústria de Transformação Alimentar, S. A.	12 175
69	-			COPAM — Indústria de Amidos e Derivados	COPAM — Companhia Portuguesa de Amidos, S. A.	13 997
70	262.01			Fromageries Bel Portugal S. A.	Fromageries Bel Portugal S. A.	14 717

Número de ordem	TEGEE (PNALE I)	Sector	Subsector	Instalação	Operador	LE (t CO2/ano)
71	037.01		Ind. Agroflorestal	Luso Finsa — Indústria e Comercio de Madeiras S. A.	Luso Finsa — Indústria e Comercio de Madeiras S. A.	4 426
72	245.01			JOMAR — I ndústrias JOMAR — Madeiras e Derivados	JOMAR — Indústrias JOMAR — Madeiras e Derivados	14 945
73	260.01			I.F.M. — Indústria de Fibras de Madeira, S. A.,	I.F.M. — Indústria de Fibras de Madeira, S. A.	10 097
74	041.01		Ind. de metais ferrosos	Lusosider -Aços Planos, S. A.,	Lusosider — Aços Planos, S. A.	29 849
75	208.01		Ind. Química	Quimigal — produção de anilina e derivados e cloro alcalis	Quimigal, Quimica de Portugal, S. A.	32 856
76	018.01			UFAA-Unidade Fabril de Adubos de Alverca	ADP-Adubos de Portugal, S. A.	8 264
77	021.01			DOW — Fabrico de matérias plásticas sob formas primárias -Isocianatos poliméricos de base MDI (metileno de DifenilIsocianato)	DOW Portugal, Produtos Químicos, SUL	48 149
78	030.01			UFAL — Unidade Fabril do Lavradio	AP — AMONÍACO DE PORTUGAL, S. A.	120 846
79	-			REPSOL Polímeros, L.da, — Fábrica de Olefinas	REPSOL Polímeros, L.da, — Fábrica de Olefinas	620 936
80	257.01			CIPAN -Companhia Industrial Produtora de Antibióticos, S. A.,	CIPAN — Companhia Industrial Produtora de Antibióticos, S. A.	5 909
81	-			CARBOGAL -Carbonos de Portugal, S. A.	CARBOGAL — Carbonos de Portugal, S. A.	119 804
82	-			Termolan 1- Vila de Aves	TERMOLAN	14 504
83	-			Termolan 2 — Sto Tirso	TERMOLAN	19 065
84	169.01		Ind. Têxtil	Riopele	Fábrica Têxtil Riopele, S. A.	4 781
85	014.01			Arco Têxteis, S..A.	Arco Têxteis, S. A.	7 088
86	002.01			TMG — Acabamentos Têxteis	TMG — Acabamentos Têxteis	17 197
87	119.01			Tinturaria e Acabamentos de Tecidos, Vale de Tábuas, L.da,	Tinturaria e Acabamentos de Tecidos, Vale de Tábuas, L.da,	8 143
88	121.01			Coelima Indústrias Têxteis, S. A.,	Coelima Indústrias Têxteis, S. A.	13 624
89	020.01			ATB-Acabamentos Têxteis de Barcelos, L.da,	ATB-Acabamentos Têxteis de Barcelos, L.da,	6 484
90	233.01			Malhas Eical	Malhas Eical	5 274
91	033.01		Outros	Tabaqueira, S. A.,	Tabaqueira, S. A.	5 833
92	031.02			Iberol — Sociedade Ibérica de Oleaginosas, S..A.	Iberol — Sociedade Ibérica de Oleaginosas, S..A.	39 488
93	142.01	Metais ferrosos	Metais ferrosos	Fábrica do Seixal da SN Seixal Siderurgia Nacional, S. A.,	SN Seixal Siderurgia Nacional, S. A.	197 292
94	150.01			Fábrica da Maia da SN Maia — Siderurgia Nacional, S. A.,	SN Maia — Siderurgia Nacional, S. A.	138 144
95	032.01	Cimentos e cal	Cal	Microlime, L.da,	Microlime — Produtos de Cal e Derivados, L.da,	37 767
96	050.01			Calcidrata	Calcidrata — Indústrias de Cal, S. A.	87 982
97	051.01			Manuel Piedade Batista e Irmão, L.da,	Manuel Piedade Batista e Irmão, L.da,	17 039
98	079.01			LUSICAL — Indústria Mineral--Calcinação de Calcários — Produção de cales não hidráulicas	Lusical — Companhia Lusitana de Cal S.A	321 234
99	105.01		Cimentos	Secil Martingança, L.da,	Secil Martingança, L.da (1)	15 718
100	175.01			Fábrica de Cal Hidráulica do Cabo Mondego	Fábrica de Cal Hidráulica do Cabo Mondego da CIMPOR — Indústria de Cimentos, S. A.	50 886
101	103.01			Fábrica Maceira-Liz	CMP — Cimentos Maceira e Pataias, S. A. (1)	762 823
102	102.01			Fábrica Secil-Outão	SECIL -Companhia Geral de Cal e Cimento, S. A. (1)	1 489 648
103	173.01			Centro de Produção de Alhandra	Centro de Produção de Alhandra da CIMPOR — Indústria de Cimentos, S. A.	1 748 681
104	172.01			Centro de Produção de Loulé	Centro de Produção de Loulé da CIMPOR — Indústria de Cimentos, S. A.	503 429
105	174.01			Centro de Produção de Souselas	Centro de Produção de Souselas da CIMPOR — Indústria de Cimentos, S. A.,	1 750 901
106	104.01			Fábrica Cibra-Pataias	CMP — Cimentos Maceira e Pataias, S. A. (1)	421 805

Número de ordem	TEGEE (PNALE I)	Sector	Subsector	Instalação	Operador	LE (t CO2/ano)
107	045.01	Vidro	Embalagem	Saint-Gobain Mondego, S. A.,	Saint-Gobain Mondego, S. A.	84 342
108	052.01			RICARDO GALLO — Vidro de Embalagem, S. A.,	RICARDO GALLO — Vidro de Embalagem, S. A.	96 530
109	049.01			Santos Barosa Vidros, S. A., -Produção e Comercialização vidro embalagem	Santos Barosa Vidros, S. A.	154 633
110	098.01			Fábrica da Marinha Grande	BA-Fábrica de Vidros Barbosa & Almeida, S. A.	147 401
111	099.01			Fábrica de Avintes		79 213
112	177.01			Sotancro, embalagem de vidro, S. A.,	Sotancro, embalagem de vidro, S. A.	58 476
113	244.01		Istalaria outros (Cr)	Fábrica de Vidros	Dâmaso-Vidros de Portugal, S. A.	12 519
114	015.01			Crisal — Cristalaria Autmoática, S. A.	Crisal — Cristalaria Autmoática, S. A.	37 746
115	044.01		Plano	Saint-Gobain Glass Portugal, Vidro Plano, S. A.,	Saint-Gobain Glass Portugal, Vidro Plano, S. A.	96 177
116	046.01	Pasta e papel	Integrado (Papel)	Soporcel	SOPORCEL — Sociedade Portuguesa de Papel, S. A.	56 467
117	023.01 024.01		Pasta e papel	Portucel -Fábricas de Pasta e de Papel de Setúbal (Complexo Industrial de Setúbal da Portucel)	PORTUCEL — Empresa Produtora de Pasta e Papel, S. A.	35 646
118	048.01		Pasta	CELBI	CELBI	62 580
119	035.01			Caima -Indústria de Celulose: Constância	Caima Indústria de Celulose, S. A.	0
120	145.01			Fábrica de CACIA	PORTUCEL — Empresa Produtora de Pasta e Papel, S. A.	32 608
121	097.01			CELTEJO -Empresa de Celulose do Tejo S. A.	CELTEJO -Empresa de Celulose do Tejo S. A.	34 079
122	087.01		Papel	Fábrica de Papel de Ponte Redonda	Manuel José de Oliveira & Cª Lda	4 881
123	063.01			Companhia de Cartões do Cávado, S. A.	Companhia de Cartões do Cávado, S. A.	3 160
124	107.01			Sociedade Transformadora de Papéis Vouga, L.da,	Sociedade Transformadora de Papéis Vouga, L.da,	3 470
125	089.01			Fapovar — Fábrica de Papel de Ovar, S. A.,	Fapovar — Fábrica de Papel de Ovar, S..A.	3 371
126	225.01			Fábrica de Papel e Cartão da Zarrinha, S. A.,	Fábrica de Papel e Cartão da Zarrinha, S. A.	8 769
127	061.01			Oliveira Santos & Irmão, L.da,	Oliveira Santos & Irmão, L.da,	2 414
128	073.01			António Marques, L.da,	António Marques, L.da,	4 407
129	064.01			Fapajal -Fábrica de papel do Tojal, S. A.	Fapajal -Fábrica de papel do Tojal, S. A.	11 503
130	096.01			CPK — Companhia Produtora de Papel Kraftsack, S. A.,	CPK — Companhia Produtora de Papel Kraftsack, S. A.,	0
131	070.01			Luís Santos & Monteiro, S. A.,	Luís Santos & Monteiro, S. A.	5 274
132	171.01			Renova -Fábrica 2	Renova — Fábrica de Papel do Almonda, S. A.	27 990
133	181.01			Joaquim Mariz de Carvalho,& CA, L.da	Joaquim Mariz de Carvalho,& CA, L.da,	2 090
134	093.01			Renova — Fábrica 1	Renova -Fábrica de Papel do Almonda SA	11 561
135	039.01			Portucel Viana	Portucel Viana, Empresa Produtora de Papéis Industriais, S. A.	20 673
136	186.01			Fábrica de Papel da Lapa, L.da,	Fábrica de Papel da Lapa, L.da,	3 424
137	088.01			Papeleira Portuguesa, S. A.,	Papeleira Portuguesa, S. A.	9 624
138	086.01			Cemopol Celuloses Moldadas Portuguesas, L.da,	Cemopol Celuloses Moldadas Portuguesas, L.da,	10 529
139	013.01			Gopaca — Fábrica de Papel e Cartão, S. A.	Gopaca -Fábrica de Papel e Cartão, S. A.	0
140	065.01			Prado-Cartolinas da Lousã, S..A.	Prado-Cartolinas da Lousã, S..A.	0
141	094.01			Prado Karton	Prado Karton -Companhia de Cartão, S. A.	16 382
142	247.01			ILHAVENSE — Soc. Industrial de Papel, L.da,	ILHAVENSE — Soc. Industrial de Papel, L.da,	4 040
143	249.01			FAPULME -Fábrica de Papel do Ulme, L.da,	FAPULME — Fábrica de Papel do Ulme, L.da,	13 378
144	084.01	Cerâmica	Tijolos, telhas e acessórios	Cerâmica Outeiro do Seixo, S. A.,	Cerâmica Outeiro do Seixo, S. A.	10 689
145	110.01			CONSTRUCER — Cerâmica de Construção, S. A.,	CONSTRUCER — Cerâmica de Construção, S..A.	408
146	111.01			CEPABIL — Cerâmica de Tijolos e Pavimentos, S. A.,	CEPABIL — Cerâmica de Tijolos e Pavimentos, S. A.	9 489

Número de ordem	TEGEE (PNALE I)	Sector	Subsector	Instalação	Operador	LE (t CO2/ano)
147	115.01			Cetipal — Cerâmica de Tijolos e Pavimentos, S. A.,	Cetipal, S. A.	7 471
148	112.01			Cerâmica F. Santiago, L.da,	Cerâmica F. Santiago, L.da,	10 062
149	131.01			Cerâmica de Santo André	Cersan 2 -Cerâmica de Coruche, L.da	196
150	116.01			A. Silva & Silva — Cerâmica, S. A.,	A. Silva & Silva -Cerâmica, S. A.	6 528
151	090.01			Empresa Cerâmica Vala	Empresa Cerâmica Vala	3 714
152	117.01			Cerâmica Certrês, L.da,	Cerâmica Certrês, L.da,	218
153	091.01			Cerâmica Rosário S. A.	Cerâmica Rosário S. A.	8 913
154	113.01			Inacer — Indústria Nacional de Cerâmica, L.da,	Cerâmica das Quintãs, L.da,	8 541
155	124.01			Cerâmica das Quintãs, L.da,	Cerâmica das Quintãs, L.da,	10 765
156	126.01			Cerâmica Domingos F. Anacleto, S. A.	Cerâmica Domingos F. Anacleto, S. A.	3 402
157	127.01			Cerâmica de Ferreirós, L.da,	Cerâmica de Ferreirós, L.da,	6 218
158	120.01			A Telheira de Chaves, L.da,	A Telheira de Chaves, L.da,	6 619
159	202.01			Sociedade Cerâmica Silmar, S. A.,	Sociedade Cerâmica Silmar, S. A.	4 616
160	139.01			Cerâmica do Centro, L.da,	Cerâmica do Centro, L.da,	8 605
161	166.01			Faceal — Fábrica de Cerâmica do Algarve	Faceal -Fábrica de Cerâmica do Algarve	6 323
162	128.01			Cerâmica de Boialvo, L.da,	Cerâmica de Boialvo,Lda	7 045
163	191.01			J. Coelho da Silva, L.da,	J. Coelho da Silva, L.da,	15 211
164	130.01			Sociedade Cerâmica do Alto, L.da,	Sociedade Cerâmica do Alto, L.da,	9 218
165	132.01			Cerâmica Castros, S. A.,	Cerâmica Castros, S. A.	8 079
166	133.01			Cerâmica Flaviense, L.da,	Cerâmica Flaviense, L.da,	3 857
167	205.01			Empresa Cerâmica Cervar, S. A.,	Empresa Cerâmica Cervar, S. A.	9 314
168	108.01			M. A. Lopes D'Avó, L.da,	M. A. Lopes D'Avó, L.da,	6 048
169	143.01			Cerâmica do Salvadorinho, S. A.,	Cerâmica do Salvadorinho, S. A.	3 485
170	154.01			Cerâmica Torreense — F4+F5	Cerâmica Torreense	13 367
171	146.01			Cerâmica da Floresta, L.da,	Cerâmica da Floresta, L.da,	5 924
172	135.01			Cerâmica Estrela D'Alva	Barbosa Coimbra, S. A.	4 418
173	136.01			Cerâmica Moderna do Olival	Cerâmica Moderna do Olival	1 424
174	185.01			Tijolar — Cerâmica do Olival, S. A.,	Tijolar — Cerâmica do Olival, S. A.	4 276
175	137.01			Cerâmica Avelar, S..A.	Cerâmica Avelar, S..A.	15 671
176	122.01			Cer. Prélis (ex- J. Monteiro e Filhos)	Cer. Prélis (ex- J. Monteiro e Filhos)	7 793
177	080.01			LUSOCERAM — Unidade Industrial de Bustos	LUSOCERAM — Empreendimentos Cerâmicos, S. A.	23 703
178	082.01			LUSOCERAM — Unidade Industrial do Ramalhal	LUSOCERAM — Empreendimentos Cerâmicos, S. A.	10 501
179	083.01			LUSOCERAM — Unidade Industrial do Outeiro	LUSOCERAM — Empreendimentos Cerâmicos, S. A.	46 112
180	151.01			Nergal	Nergal — Nova Cerâmica Algarvia Lda	5 116
181	157.01			F. S. e Cerâmica Amaro de Macedo, S. A.	F. S. e Cerâmica Amaro de Macedo, S. A.	3 306
182	140.01			Cerâmica Vicente e Filhos, L.da,	Cerâmica Vicente e Filhos, L.da,	5 446
183	183.01			Campos- Fábricas Cerâmicas, S. A.,	Campos- Fábricas Cerâmicas, S. A.	18 019
184	180.01			Cerâmica Sotelha, S. A.,	Cerâmica Sotelha, S. A.	12 987
185	160.01			A Tijoleira Central de Estarreja, L.da,	A Tijoleira Central de Estarreja, L.da	5 068
186	161.01			CERAVE — Cerâmica Avelense, S. A.	CERAVE — Cerâmica Avelense, S..A.	356
187	199.01			Cerâmica Condestável, L.da,	Cerâmica Condestável, L.da,	7 179
188	193.01			Cerâmica das Alhadas, S. A.,	Cerâmica das Alhadas, S. A.	7 775
189	215.01			Empresa de Cerâmica da CARRIÇA, S. A.	Empresa de Cerâmica da CARRIÇA, S. A.	5 546
190	227.01			Cosbar	Cosbar — Cerâmica do Barlavento, S. A.	7 065
191	148.01			Abílio Duarte da Mota & Filhos, L.da,	Abílio Duarte da Mota & Filhos, L.da	12 799
192	149.01			Abílio Duarte da Mota, L.da,	Abílio Duarte da Mota, L.da,	6 006
193	228.01			Cerâmica do Planalto — Variz	Cerâmica do Planalto, L.da,	11 656
194	152.01			Unidade Industrial da Chamusca	Faceril — Fábrica de Cerâmica do Ribatejo, S. A.	4 348
195	165.01			Unidade Industrial de Mortágua	Cerâmica Vale da Gândara, S..A.	6 210
196	210.01			Martelha, L.da,	Martelha — Cerâmica de Martingança, L.da	6 107
197	156.01			Cerâmica de Pegões	Cerâmica de Pegões — J. G. Silva, S. A.	6 339
198	164.01			CERPOL — Empresa Cerâmica Portugal, S. A.,	CERPOL — Empresa Cerâmica Portugal, S. A. (2)	5 901
199	212.01			Cerâmica da Cruz do Campo	Iberoceram	8 623
200	229.01			Cerâmica Central do Algoz, L.da,	Cerâmica Central do Algoz, L.da,	4 206
201	155.01			Cerâmica Torreense — F3	Cerâmica Torreense	9 771
202	230.01			Grésil	Grésil	1 852
203	195.01			Lusotelha, Telhas e Tijolos de Águeda, L.da	Lusotelha, Telhas e Tijolos de Águeda, L.da	6 200
204	231.01			Cerâmica Ulmense, L.da,	Cerâmica Ulmense, L.da,	7 310
205	179.01			ECC — Empresa Cerâmica de Candosa, L.da,	ECC — Empresa Cerâmica de Candosa, L.da,	703

Número de ordem	TEGEE (PNALE I)	Sector	Subsector	Instalação	Operador	LE (t CO2/ano)
206	236.01			Preceram — Cerâmica 1	Preceram — Indústrias de Construção S. A.	20 299
207	237.01			Preceram — Cerâmica 2	Preceram — Indústrias de Construção S. A.	14 264
208	239.01			Preceram Norte (ex- Fabricel)	Preceram — Norte, Cerâmicas, S. A.	12 801
209	221.01			Tijolágueda — Cerâmica de Águeda — Lda	Tijolágueda — Cerâmica de Águeda — Lda	16 547
210	268.01			Placfort — Empresa de Pré-esforçados, S. A.	Placfort — Empresa de Pré-esforçados, S. A.,	347
211	207.01		Pisos e azulejos	Soladrilho, S. A.	Soladrilho, S. A.	13 052
212	192.01			Grestejo, Indústrias Cerâmicas, S. A.	Grestejo, Indústrias Cerâmicas, S. A.	6 201

Annex II – List of identified carbon dioxide LPS and related carbon dioxide emission allowances of Spain´s power sector

Energy/Power plants	Coal	Endesa Generación, S.A. - Puentes	Rodríguez (A Coruña)	4.501.674
	Coal	Endesa Generación - Teruel 1, 2 y 3	Andorra (Teruel)	4.107.596
	Coal	Endesa Generación, S.A. - Compostilla	Cubillos del Sil (León)	3.560.306
	Coal	Endesa Generación-Litoral	Carboneras (Almería)	3.367.031
	Coal	Hidrocantábrico S.A -Aboño 1 y 2	Gijón (Asturias)	2.854.812
	Coal	Generación, S.A - La Robla	La Robla (León)	1.783.630
	Coal	Endesa Generación - Los Barrios	Los Barrios (Cádiz)	1.740.776
	Coal	Generación. S.A -Meirama	Ordes (A Coruña)	1.727.586
	Coal	Soto Ribera 1, 2 y 3	Ribeira de Arriba (Asturias)	1.588.431
	Coal	Unión Fenosa Generación. S.A -Narcea 1, 2 y 3	Tineo (Asturias)	1.455.129
	Coal	C.T. Anllares	Páramo del Sil (León)	1.135.510
	Coal	Iberdrola Generación, S.A.U. - Grupo 1 - Central térmica Velilla del Río Carrión, grupo 1	Velilla del Río, Carrión (Palencia)	1.106.409
	Coal	Iberdrola Generación, S.A.U. - Lada 3 y 4	La Felguera (Asturias)	1.067.199
	Coal	Viesgo Generación - Puente Nuevo	Espiel (Córdoba)	992.301
	Coal	Viesgo Generación -Puertollano	Puertollano (Ciudad Real)	593.988
	Coal	Viesgo Generación -Escucha	Escucha (Teruel)	377.317
	Coal	Iberdrola Generación, S.A.U. - Grupo 1 - Central térmica Velilla del Río Carrión, grupo 1	Velilla del Río, Carrión (Palencia)	338.319
	Coal	Iberdrola Generación, S.A.U. - Pasajes	Pasaia (Guipúzcoa)	120.668
	Islands[1]	Gas y Electricidad Generación, S.A.U. -Alcudia	Alcúdia (Illes Balears)	2.171.552
	Islands[1]	Unión Eléctrica de Canarias Generación -C.T. Barranco de Tirajana	San Bartolomé de Tirajana (Las Palmas)	1.121.421
	Islands[1]	Unión Eléctrica de Canarias Generación -C.T. Granadilla	Granadilla de Abona (Santa Cruz de Tenerife)	1.107.660
	Islands[1]	Unión Eléctrica de Canarias Generación -C.T. Jinámar	Las Palmas de Gran Canaria (Las Palmas)	562.590
	Islands[1]	Unión Eléctrica de Canarias Generación -C.T. Candelaria	Candelaria (Santa Cruz de Tenerife)	380.690
	Islands[1]	Gas y Electricidad Generación S.A.U. -C.T. Son Reus	Palma de Mallorca (Illes Balears)	364.929
	Islands[1]	Unión Eléctrica de Canarias Generación -C.D. Punta Grande	Arrecife (Las Palmas)	272.355
	Islands[1]	Gas y Electricidad Generación, S.A.U. -C.T. Eivissa	Eivissa (Illes Balears)	249.593
	Islands[1]	Gas y Electricidad Generación S.A.U. -C.T. Cas Tresorer	Palma de Mallorca (Illes Balears)	218.072
	Islands[1]	Unión Eléctrica de Canarias Generación -C.D. Las Salinas	Puerto del Rosario (Las Palmas)	217.069

	Islands[1]	Gas y Electricidad Generación, S.A.U. -Maó	Mahón (Illes Balears)	163.471
	Islands[1]	Unión Eléctrica de Canarias Generación -Central eléctrica Los Guinchos	Breña Alta (Santa Cruz de Tenerife)	101.342
Energy/Cogeneration	Combined cycle	Gas Natural, S.D.G., S.A. - Escombreras 1, 2 y 3	Cartagena (Murcia)	968.711
	Combined cycle	Generación, S.A. -Sagunto 1, 2 y 3	Sagunto (Valencia)	929.523
	Combined cycle	Unión Fenosa Generación, S.A. - Palos de la Frontera I- 1, I-2 y II-3	Palos de la Frontera (Huelva)	906.277
	Combined cycle	AES Energía Cartagena, S.R.L. -Escombreras	Cartagena (Murcia)	899.050
	Combined cycle	Gas Natural, S.D.G.,S.A. - La Plana de Vent 1 y 2	Vandellòs i L'Hospitalet de L'Infant (Tarragona)	656.313
	Combined cycle	Iberdrola Generación, S.A.U. - Arcos de la Frontera II-1 y II-2 (grupo 3)	Arcos de la Frontera (Cádiz)	639.371
	Combined cycle	Endesa Generación, S.A. - As Pontes (ciclo Generación ciclo combinado)	Rodríguez (A Coruña)	637.769
	Combined cycle	Iberdrola Generación, S.A.U. - Escombreras ciclo combinado 1 y 2 (grupo 6)	Cartagena (Murcia)	621.216
	Combined cycle	Nueva Generadora del Sur	San Roque (Cádiz)	620.829
	Combined cycle	Castelnou Energía, S.L. 1 y 2	Castelnou (Teruel)	608.868
	Combined cycle	Bizkaia Energía, S.L -Amorebieta 1 y 2	Amorebieta (Vizcaya)	607.036
	Combined cycle	Bahía Bizkaia Electricidad - BBE 1y 2 (IB, BP, Repsol)	Zierbena (Vizcaya)	606.357
	Combined cycle	Iberdrola Generación, S.A.U. - Castellón ciclo combinado 3-1 y 3-2	Grao de Castellón (Castellón)	605.326
	Combined cycle	Gas Natural, S.D.G., S.A. - Arrubal 1 y 2	Arrúbal (La Rioja)	603.006
	Combined cycle	Endesa Generación S.A. - Besòs (Endesa Ciclos Generación ciclo combinados, S.L. - Besos 3)	Sant Adrià de Besòs (Barcelona)	320.006
	Combined cycle	Generación ciclo combinados, S.L. - San Roque 2	San Roque (Cádiz)	311.566
	Combined cycle	Gas Natural, S.D.G., S.A. - Besos 4	Sant Adrià de Besòs (Barcelona)	310.284
	Combined cycle	Endesa Generación, S.A. - Tarragona (Tarragona 1 Endesa)	Tarragona	309.037
	Combined cycle	Iberdrola Generación, S.A.U. - Santurce (grupo 4)	Santurtzi (Vizcaya)	307.277
	Combined cycle	Unión Fenosa Generación, S.A. - Sabón I-1	Arteixo	305.262
	Combined cycle	Eléctrica de la Ribera del Ebro. S.A - Castejón I-1	Castejón (Navarra)	304.690
	Combined cycle	Endesa Ciclos Combinados, S.L. - Cristóbal Colon	Huelva	303.690
	Combined cycle	Iberdrola Generación, S.A.U. - Arcos de la Frontera I-1	Arcos de la Frontera (Cádiz)	301.904
	Combined cycle	Gas Natural, S.D.G., S.A. - San Roque 1	San Roque (Cádiz)	301.576
	Combined cycle	Iberdrola Generación, S.A.U. - Aceca 3	Villaseca de la Sagra (Toledo)	298.798
	Combined cycle	Fuerzas Eléctricas de Navarra, S.A.U -Castejón 2	Castejón (Navarra)	293.517
	Combined cycle	Iberdrola Generación, S.A.U. - Arcos de la Frontera I-2	Arcos de la Frontera (Cádiz)	289.510

	Combined cycle	Unión Fenosa Generación, S.A. - Aceca 4	Villaseca de la Sagra (Toledo)	285.298
	Combined cycle	Global 3 Combi., S.L.U., C. Peaker Escatrón (**)	Escatrón (Zaragoza)	147.289

[1] Islands: Power plants which are situated on Spanish islands (Baleares and Canaries)